TYPOLOGY AND FORMATION OF POTHOLE ALONG THE MEKONG RIVER AND EROSIONAL REMNANT IN SANDSTONE OF KHORAT GROUP, UBON RATCHATHANI PROVINCE, NORTHEASTERN THAILAND

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การจำแนกและการก่อรูปแบบของกุมภลักษณ์ตามแนวแม่น้ำโขงและส่วนที่เหลือจากการกร่อนในหินทรายของกลุ่มหินโคราชจังหวัดอุบลราชธานี ภาคตะวันออกเฉียงเหนือ ประเทศไทย

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ในพื้นที่อุทยานธรณีผาชัน สามพันโบก ภาคตะวันออกเฉียงเหนือของประเทศไทย จังหวัดอุบลราชธานี บริเวณริมแม่น้ำโขงระหว่างรอยต่อของประเทศไทยและประเทศลาวพบลักษณะรูปแบบของการกัดกร่อนของหินทรายที่น่าสนใจคือ การเกิดโบกจำนวนมากในแม่น้ำโขงและการเกิดเสาเฉลียงที่ใหญ่ที่สุดในประเทศไทย โดยโบกเกิดจากการขัดสีของตะกอนโดยกระแสน้ำวนในรอยแตก ในงานวิจัยนี้ได้ศึกษาการวิวัฒนาการของการเกิดโบก จึงสามารถจำแนกรูปแบบของโบกที่เกิดในแม่น้ำโขงออกมาได้สองกลุ่มหลักได้แก่ โบกที่ถูกควบคุมโดยโครงสร้างทางธรณีและ โบกที่ไม่ถูกควบคุมโดยโครงสร้างทางธรณี ซึ่งโบกรูปแบบนี้แบ่งออกได้อีก 5 รูปแบบย่อย ได้แก่ โบกทรงรี โบกด้านข้าง โบกด้านข้างแบบเปิด โบกลำดับชั้น และโบกเชื่อมประสาน กรวดในชั้นหินทรายถูกนับและเปรียบเทียบกับองค์ประกอบของกรวดที่อยู่ในโบกและแสดงถึงความสัมพันธ์ว่ายิ่งปริมาณกรวดมาก การเกิดโบกก็จะเกิดขึ้นได้ง่ายตาม มีการสร้างลำดับชั้นหินในพื้นที่ศึกษาโดยบรรยายถึงชุดลักษณะของหินและโครงสร้างของหินตะกอน รวมถึงการเกิดโบกยังมีความเกี่ยวข้องกับหินทรายปนกรวดที่เป็นต้นกำเนิดกรวดในโบกและโครงสร้างชั้นเฉียงระดับแบบร่องทำให้เกิดโบกแบบลำดับชั้น มีการใช้โดรนบินในรูปแบบตารางเพื่อบันทึกภาพถ่ายทางอากาศเพื่อประเมินความหนาแน่นของโบกโดยแบ่งได้ 3 เขต เขตความหนาแน่นสูง กลาง และต่ำ สามพันโบกถูกควบคุมด้วย 3 ปัจจัยหลักคือ การวางตัวของชั้นหินในแนวระนาบ ความแรงของกระแสน้ำจากแม่น้ำที่แคบลง และที่ตั้งอยู่บริเวณโค้งด้านนอกของแม่น้ำที่มีการกัดเซาะสูง นอกจากนี้ยังมีการศึกษาการเกิดเสาเฉลียง พบว่าเกิดจากการกัดกร่อนโดยทางน้ำโบราณลงไปตามรอยแตกที่เป็นผลมาจากการยกตัวของเปลือกโลก การศึกษาชุดลักษณะของหินซึ่งบอกได้ว่าชั้นหินบริเวณนี้เกิดการสะสมตัวในแม่น้ำประสานสายและมีทิศทางการไหลไปทางทิศตะวันตกเฉียงใต้ สุดท้ายงานวิจัยนี้ยังชี้ให้เห็นถึงจุดเด่นทางธรณีที่สามารถผลักดันพื้นที่นี้ไปสู่อุทยานโลกได้ รวมถึงข้อเสนอแนะถึงชุมชนรวมถึงการจัดการความเสี่ยงของพื้นที่ผาชันและสามพันโบกในอนาคต

สาขาวิชา	ธรณีวิทยา	ลายมือชื่อนิสิต	....
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KEYWORD: pothole, Samphanbok, pedestal rock, Geopark, Mekong river

Sirawat Udomsak : TYPOLOGY AND FORMATION OF POTHOLE ALONG THE MEKONG RIVER AND EROSIONAL REMNANT IN SANDSTONE OF KHORAT GROUP, UBON RATCHATHANI PROVINCE, NORTHEASTERN THAILAND. Advisor: Prof. Montri Choowong, Ph.D. Co-advisor: Asst. Prof. Vichai Chutakositkanon, Ph.D.

Phachan Samphanbok Geopark showcases fascinating erosional features, such as a multitude of potholes in the Mekong River. Additionally, it is home to the largest pedestal rock in Thailand, located in Ubon Ratchathani province in the northeastern part of the country, near the border between Thailand and Laos PDR. The formation of potholes is attributed to the erosive force of swirling sediment within fractures caused by vortex currents. In this research study on pothole evolution, the potholes in the Mekong River were categorized into two main groups: structural control potholes and non-structural control potholes. These types were further divided into five groups: ovoid potholes, lateral potholes, open lateral potholes, hierarchical potholes, and coalesced potholes. To analyze pothole characteristics, pebbles within sandstone beds were counted, and samples of pothole grinders were collected for composition comparison. The study revealed that a higher proportion of grinders in a pothole increases the likelihood of its occurrence. Stratigraphic columns were constructed in the study area to describe lithofacies and sedimentary structures. Pothole occurrence was found to be related to pebbly sandstone and trough cross bedding, which are associated with hierarchical potholes. A drone was utilized to capture aerial photos in a grid pattern, enabling the estimation of pothole density and categorization into three zones: high-density, moderate-density, and low-density pothole zones. Several factors were identified as controlling pothole occurrence, including horizontal bedding, the narrow width of the river leading to increased flow velocity, and the location situated in the cutbank zone. The formation of the giant pedestal rock is attributed to ancient gullies eroding into vertical fractures during the last tectonic event. The study of lithofacies indicates a paleoenvironment characterized by a braided river, with paleocurrents flowing in a southwest direction. Overall, this research emphasizes the significance of promoting the Phachan Samphanbok Geopark as a world-class geological heritage site. It also provides suggestions for the local communities and recommendations for future risk management in the Phachan and Samphanbok areas.

Field of Study: Geology		Student's Signature ....
Academic Year: 2022		Advisor's Signature ....
		Co-advisor's Signature ....

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Furthermore, I want to extend my heartfelt gratitude to my parents for their wise guidance and empathetic listening. They have always been there for me whenever I needed their support. The completion of this thesis would not have been possible without the help and encouragement of my friends.

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CHAPTER 1

INTRODUCTION

The primary aim of this dissertation is to conduct a comprehensive analysis of the typology and formation of potholes along the Mekong River and erosional remnants in the sandstone of the Khorat Group. The research will focus on understanding the various processes that lead to the formation of these geological features and their characteristics.

To provide a better understanding of the research area, the introduction chapter of this thesis will offer detailed information on various topics, including the UNESCO geopark and geopark in Thailand, the research area at Samphanbok and pedestal rock, Ubon Ratchathani's geological background and stratigraphy, as well as previous research related to the formation of potholes and erosional remnants in the region.

Through this research, we hope to contribute to the current understanding of the geology of the Khorat Group and the Mekong River region. The findings of this dissertation will provide valuable insights into the processes involved in the formation of potholes and erosional remnants and will serve as a foundation for future research in this field.

1.1 Geoheritage

The term "Geoheritage" refers to locations or areas that possess significant scientific, educational, cultural, and/or aesthetic value due to their unique geological characteristics. (https://www.americasgeoheritage.com/geoheritage/). The primary focus of this article is on the UNESCO Geopark and the geopark located in Thailand.

1.1.1 UNESCO Global Geopark

UNESCO Global Geoparks are geographical areas that contain sites and landscapes of international geological significance, which are managed in a comprehensive manner that encompasses preservation, education, and sustainable development. The geoparks' bottom-up approach, which involves local communities and integrates conservation with sustainable development, is gaining popularity. Currently, there are 177 UNESCO Global Geoparks across 46 countries.

UNESCO began collaborating with geoparks in 2001. In 2004, representatives from all 17 European and 8 Chinese geoparks convened at UNESCO's headquarters in Paris to establish the Global Geopark Network (GGN). The GGN enables national geological heritage initiatives to participate in a global exchange and collaboration network, promoting the sharing of knowledge and experiences. Its main aim is to establish best practice models and quality standards for territories that integrate the preservation and protection of Earth heritage sites into regional sustainable economic development strategies.

There are a total of eleven UNESCO Geoparks located in Southeast Asia, which are spread across Thailand, Vietnam, Malaysia, and Indonesia. The first UNESCO Geopark in Thailand, Satun Global Geopark, was certified on April 17, 2018, and has since become a member of UNESCO Global Geoparks. Mountains and foothills in the eastern and northern regions characterize the landscape of Satun Geopark, while the western region faces the Andaman Sea, featuring beaches and coastal islands as shown in Figure 1.1. Satun Geopark is renowned for its rich Paleozoic fossil deposits. Tarutao Island, which is part of Satun Geopark, is home to the oldest Cambrian trilobite fossils on the Thai-Malay Peninsula, and the volcanic ash layers present on the island allow for precise dating of late Cambrian trilobite biostratigraphy.

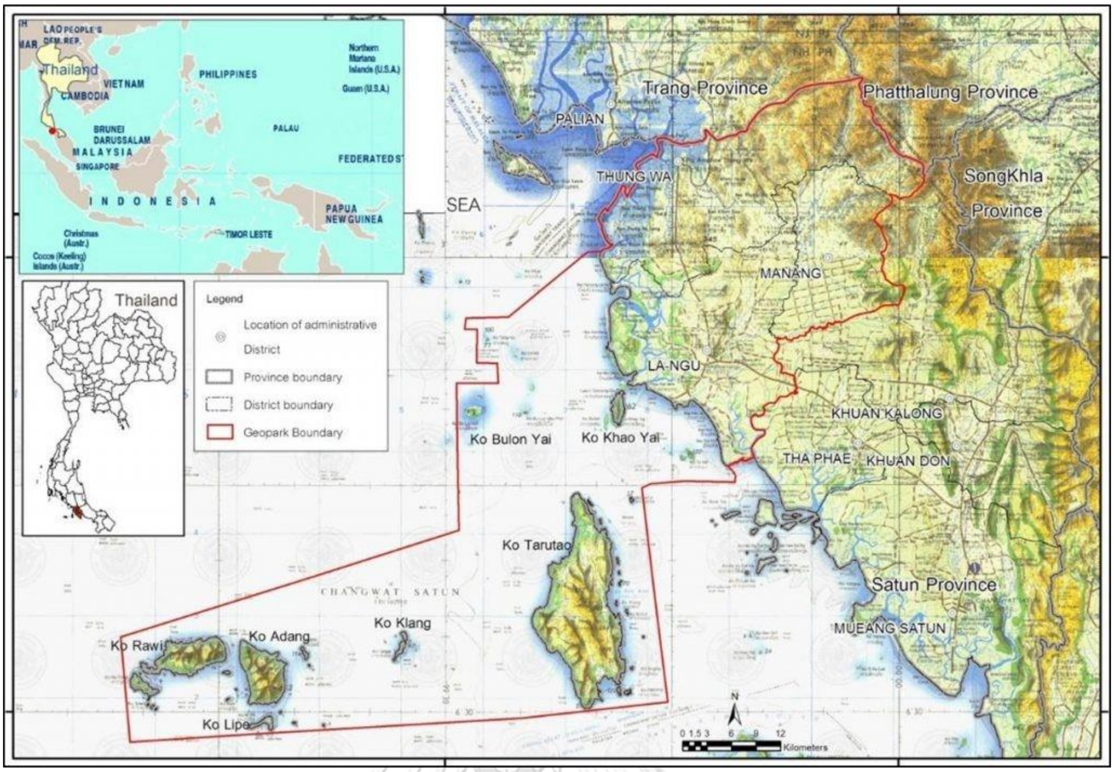


Figure 1.1 The map of Satun Geopark, which is located in Satun Province. (http://satun.nfe.go.th/satungeopark/index.php?name=knowledge1&file=readknowledge&id=41)

1.1.2 Geoparks in Thailand

Thailand launched the Geopark initiative in 2010 with the objective of promoting development, education, and conservation in designated areas, while also attracting tourists and generating revenue for local communities. To qualify as a UNESCO Geopark, a site must possess archaeological, ecological, and cultural significance, in addition to geological importance. On November 29, 2016, Satun Geopark in the province of Satun became Thailand's first geopark. The karst topography and Precambrian fossils are the attractive highlights of this geopark. On August 24, 2018, Khorat Geopark was subsequently granted geopark status, showcasing the uplift and formation of the cuesta sandstone mountain from the Khorat plateau and housing 10 different species of ancient elephant fossils. Phachan and Samphanbok, initially designated as a local geopark in 2011, were officially granted geopark status on August 22, 2019. The Phachan sandstone cliff, stretching along the Mekong River for around 3 kilometers, features the largest pedestal rock in Thailand, revealing evidence of wind and water erosion. The presence of thousands of potholes highlights the Mekong River canyon, known as Samphanbok.

1.2 Study Area

1.2.1 Samphanbok and Pedestal rock, Ubon Ratchathani

Samphunbok, a local geographic name, refers to a famous pothole site that has gained significant attention over the years. This site, as depicted in Figure 1.2, has now been recognized and registered as a provincial natural conservation place. According to Figures 1.3a and c, Samphunbok is located in Pho Sai district, which lies 120 kilometers north of Ubon Ratchathani province, and is situated at the border between Thailand and Laos PDR. The canyon, which stretches over a length of approximately 30 square kilometers along the Mekong River, as shown in Figure 1.3d, has earned the moniker of the Grand Canyon of Thailand, due to its magnificence.

The area owes its fame to the numerous potholes that have formed on an outcropping of sandstone within the Mekong River. The name 'Samphunbok' originates from the local language and translates to '3,000 holes,' reflecting the vast number of potholes present at this site. The vertical erosion, caused by running water inside the canyon where the Mekong River is located, has played a crucial role in shaping the landscape and creating the potholes.

One of the unique features of the Samphunbok area is the presence of a giant pedestal rock, which is the largest mushroom-like rock on the Khorat Plateau in Ubon Ratchathani. The rock's mushroom-like shape is attributed to the difference in the degree of weathering and erosion in a weak point of thick bed sandstones. This formation is not the only sign of erosion in the sandstone of the Khorat Group, which is in the same area as the pothole site.

Overall, Samphunbok has become a significant tourist attraction in Thailand due to its breathtaking beauty and geological importance. The area's preservation and conservation have been prioritized, and it has been registered as a natural conservation place, ensuring that it remains a destination for generations to come.

Figure 1.3c illustrates that the Phu Phan Formation of the Khorat Group sandstone encompasses both Samphunbok and the giant pedestal rock. The formation is estimated to have formed in the early Cretaceous period. White sandstone dominates the lithology of the Phu Phan Formation, which includes greyish-white coarse-grained sandstone to conglomerate with trough and planar cross bedding. Geological evidence suggests that the paleoenvironment of this formation was a braided river, while the paleoclimate is considered to have been semi-arid. (Meesook, 2011).

At Samphunbok, a sedimentary process eroded several thousands of potholes of various dimensions underwater during bank-full discharge in the Mekong River. Therefore, the hypothesis of this dissertation is set up that potholes were formed by the rotary grinding motion of sand, pebbles, or boulders derived from weathered sandstone itself in the depression of channel bedrocks (Alexander, 1932; Ji, Li, and Zeng, 2018). The giant pedestal rock was possibly formed by erosion and weathering of thick bed sandstone of the Khorat Group, and the resistance bed became the cap rock (Bryan, 1926). Its formation process may relate to the regional scale uplifted of the Khorat Plateau. To better understand the typology and formation of the potholes and the giant pedestal rock, the research objectives of this study are to investigate the stratigraphy and lithology of pothole formation at Samphunbok and the giant pedestal rock. The expected output is to demonstrate the evolution of potholes and the erosional features of the giant pedestal rock as a case study of the region.

Figure 1.2 Spectacular potholes field at Sam Pan Bok, Canyon liked channel at Pho Sai district, Ubon Ratchathani province, northeastern Thailand and taken from a southeastern perspective.

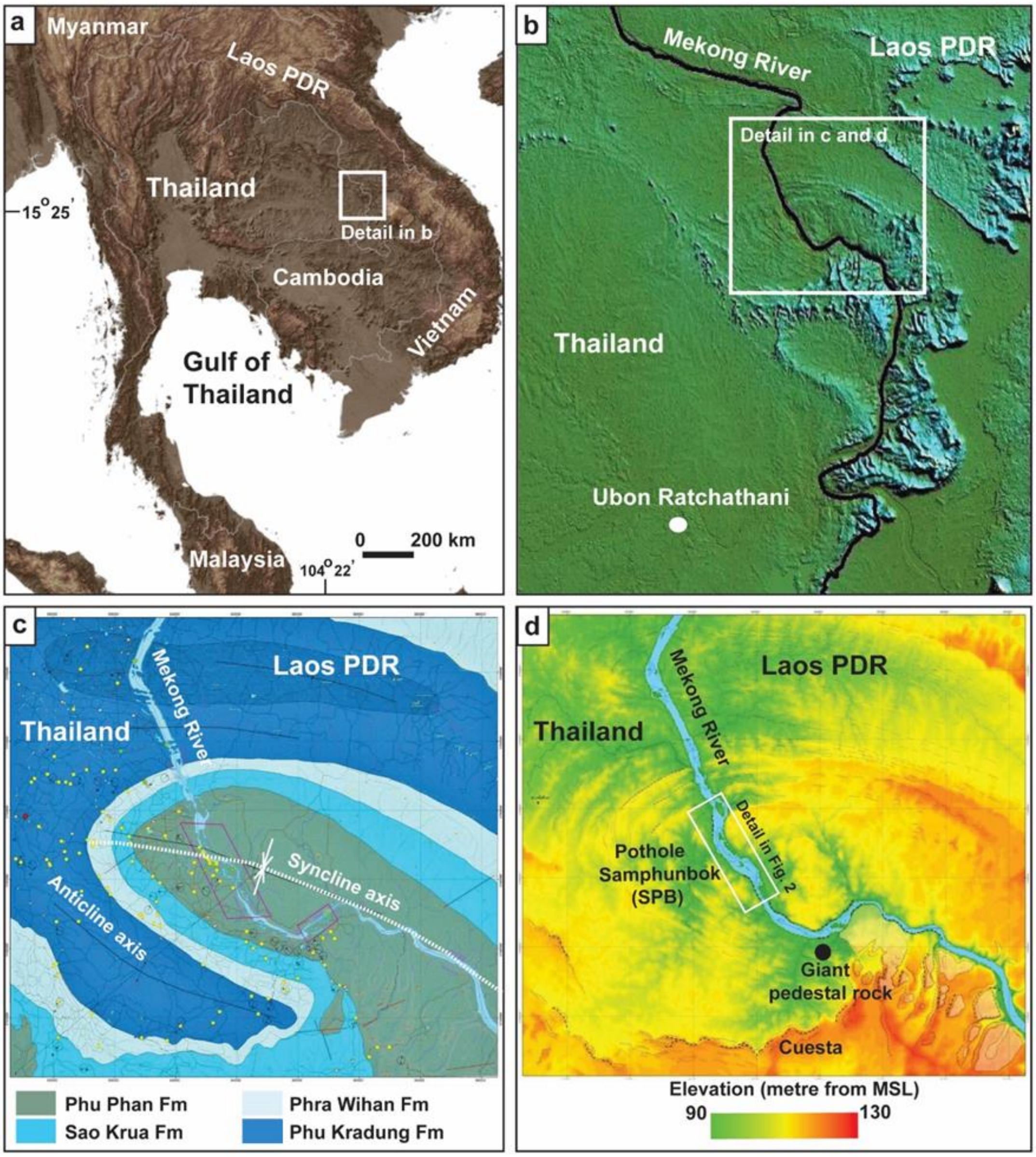


Figure 1.3 The following information is displayed on the maps: a) The position of Samphunbok within Ubon Ratchathani Province. b) The location of Samphunbok on the border of Thailand and Laos. c) The picture modified from Choowong et al. (2013) show the composition of Khorat Group sandstone in Samphunbok, which includes the Phu Kradung Formation, Phra Wihan Formation, Sao Khua Formation, and Phu Phan Formation and yellow spot are samples collecting location of. d) A topographic map of the Samphunbok region, which shows the geomorphology of Thailand and Laos.

1.2.2 Geological Setting and Stratigraphy

The Khorat Plateau is in the northeastern part of Thailand. There are many cuesta and mesa landforms because of the weathering and erosion processes of continental Mesozoic sandstone (Choowong et al., 2013). Racey (2009) says that the Khorat Group is a non-marine sandstone bed that dates back to the Mesozoic. It was deposited in the northeastern part of Thailand and expanded to Laos and Cambodia. The thickness of this sandstone is around 4.5 km. The Samphunbok area consists of the Phra Wihan, Sao Khua, and Phu Phan Formations, which are all part of the Khorat Group sandstone. The thickness of the Phra Wihan Formation ranges from about 50 to 300 meters. The braided river was the paleoenvironment at the time. The Sao Khua Formation is approximately 100 to 700 meters thick, and its paleoenvironment was an alluvial floodplain. The Phu Phan Formation's thickness ranges from around 50 to 100 meters, and its paleoenvironment was characterized by braided rivers.

The Champa Formation in the Vientiane Basin, the Bang Fai Formation in the Savannakhet Basin, and the Phu Phan Formation in the Khorat Basin have equivalent ages. The Phu Phan Formation, which dates back to the early Cretaceous period, has paleocurrent equivalents to the Bang Fai Formation in the Savannakhet Basin in Laos PDR, where the currents mainly flow southwest. The thickness of the Phu Phan Formation is greater in the west than in the east, as seen in Figure 1.4.

The Khorat plateau is comprised of two basins, namely the Sakon Nakhon basin in the northeast and the Khorat basin in the south, which are separated by the Phu Phan ridge. The Phu Phan ridge, which runs in a northwest-southeast direction, is a fold in the Mesozoic rock, as seen in Figure 1.5, and it formed during the Himalayan orogeny resulting from the collision of the Indian-Australian and Eurasian plates. This collision caused a clockwise tectonic shift into Southeast Asia during the early Tertiary period. (Sattayarak, Srigulwong, and Patarametha, 1991). The only evidence of a tectonic event in the Samphunbok area is the syncline structure.

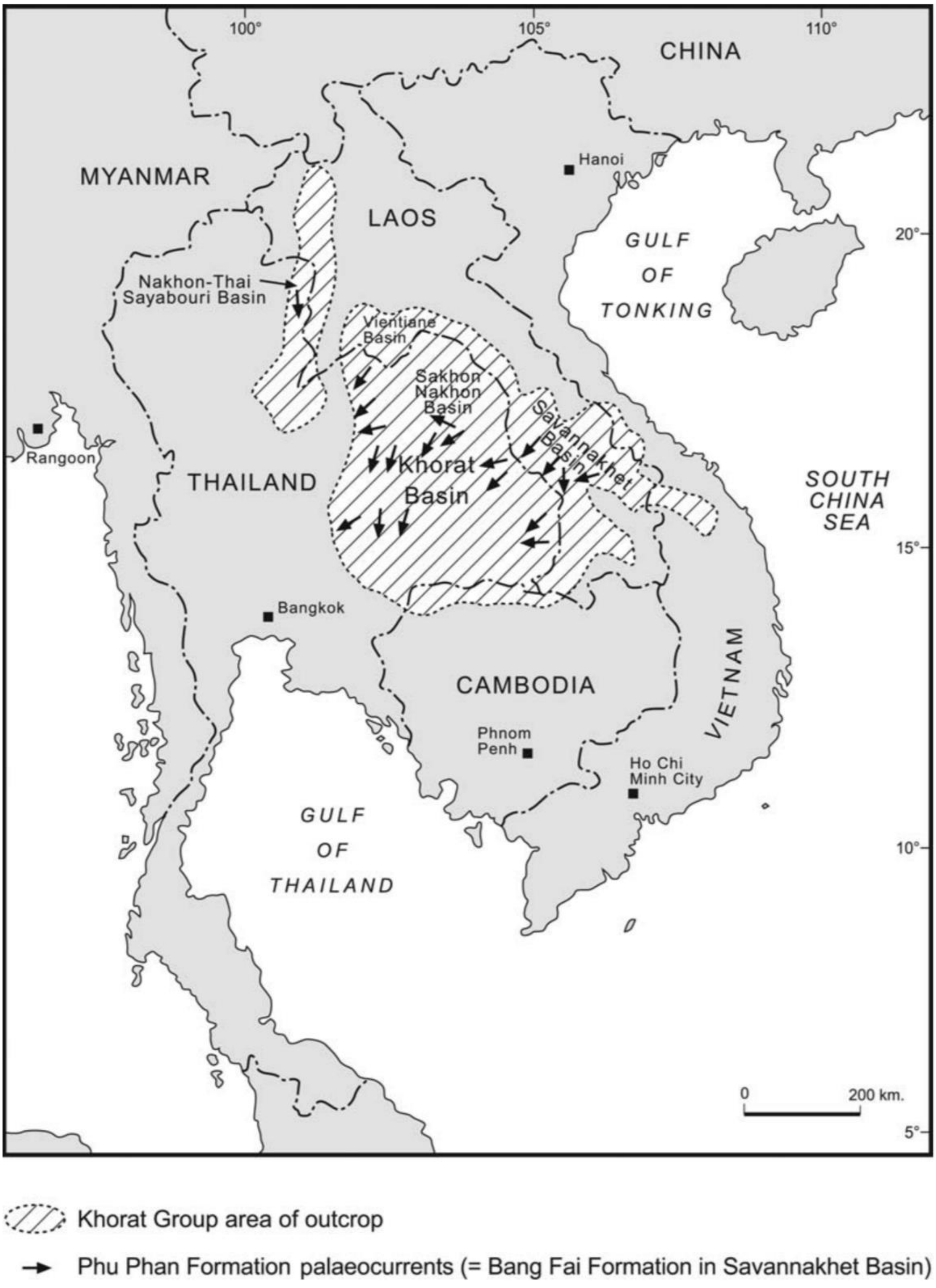


Figure 1.4 The Phu Phan Formation and its equivalent formation in Laos PDR exhibit paleocurrents in a southwest direction. (Racey, 2009)

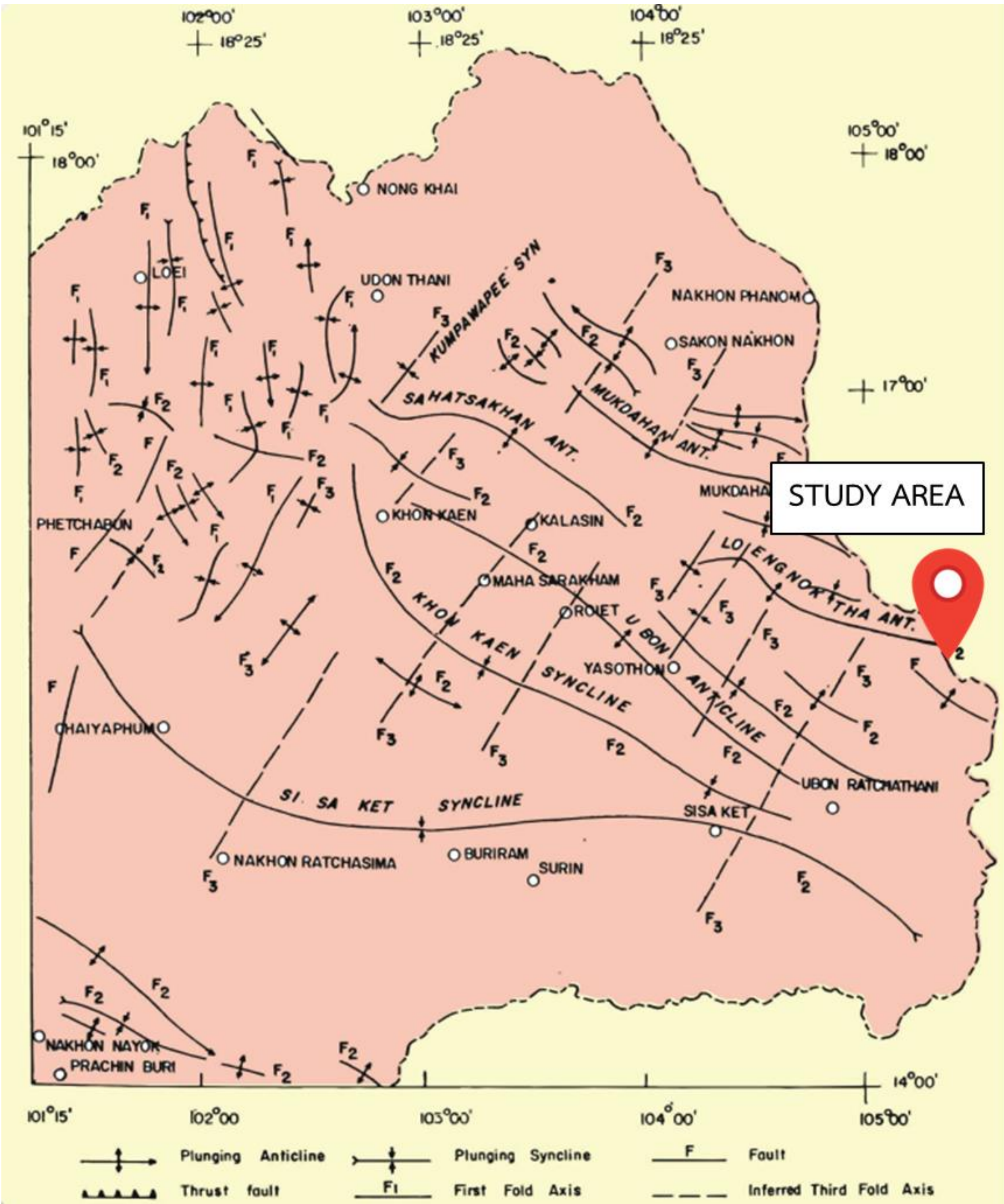


Figure 1.5 The map depicts the structural geology of Mesozoic rocks resulting from tectonic events in the Indochina plate. (Chuaviroj, 1997)

At the Samphanbok Geological Heritage Site, the Mekong River's water level is closely tied to the stability of the sandstone bed and the formation of potholes. The river's level varies throughout the year due to seasonal changes in weather patterns. From December to April, the river's level is typically lower than the sandstone bed 1, which has been identified through stratigraphy at the site. However, in April, the river level begins to rise as a result of summer thunderstorms.

The highest water level of the Mekong River at Samphanbok occurs during August and September, which is the rainy season in the region. During this time, heavy rains cause the river to swell and reach its peak level. As the rainy season comes to an end in October, the river level gradually starts to decrease, and this trend continues into December, which marks the start of the winter season (Chua et al., 2021; Thanh et al., 2020) (Figure 1.6).

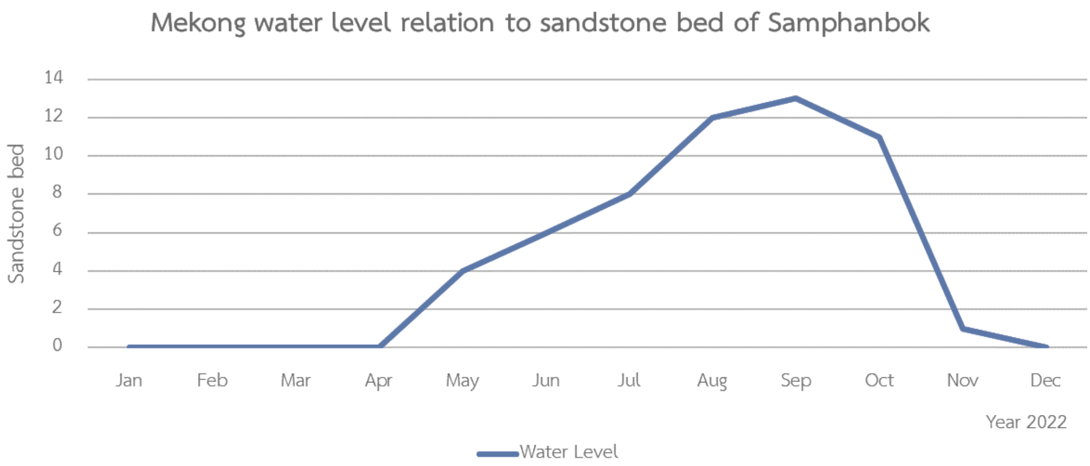


Figure 1.6 The diagram showing the Mekong River level related to the bed rock in the stratigraphy of Samphanbok.

1.2.3 Previous Study

According to Choowong et al. (2013) , the potholes at Samphanbok are located in the Phu Phan Formation of the Khorat Group sandstone. The lithology of this formation is medium to pebbly sandstone, with basal conglomerate in mega cross bedding. Samphanbok has a pothole located in the middle of a syncline that has a dip angle of bedding less than 5 degrees. The potholes at Samphanbok can be classified into six types based on their shape, such as pot shape, curve and long shape, large pool shape, sinkhole-like cave shape, straight and connected shape, and u-shaped valley or canyon shape. Pot shape potholes occur on the surface of the stone as seen in Figure 1.7a, while curve and long shape potholes occur related to sedimentary structures such as joints or fractures as seen in Figure 1.7b. Many potholes erode horizontally and combine to form large pool shape potholes in Figure 1.7c.

Richardson and Carling (2005) conducted a study on the classification of bedrock bedforms at The Ob Luang in northern Thailand, as shown in Figure 1.9. They identified that potholes are among the concave features of bedrock, as seen in Figure 1.8a and b. The term "concave feature" refers to a sculptural form that can be found on the exposed bedrock in the channel. Potholes in this region affect granite and gneissic granite and can be categorized into five types, which will be discussed in detail in Chapter 2 literature review.

The Phu Phan Formation has a thickness of approximately 80-140 meters and is composed of medium to coarse-grained sandstone with some beds consisting of conglomerate. This formation displays large planar and trough cross bedding as its primary sedimentary structures. Due to the resistance of the coarse-grained beds to weathering and erosion, the Phu Phan Formation is typically found at the top of cuestas and mesas, with pedestal rocks being present in some areas (Department_of_Mineral_Resources, 2014). These are formed by differential erosion on sandstone and shale terrain, with the neck of the pedestal rock being more resistant to weathering due to the presence of iron oxide, forming a cap rock (Nocita, 1986).

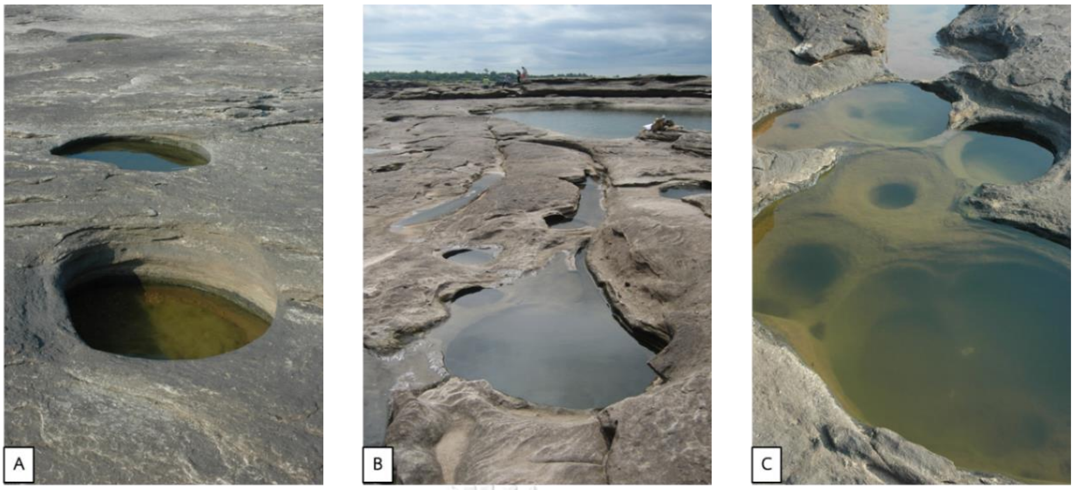


Figure 1.7 The photograph depicts different types of potholes: a) pot-shaped potholes occurring on the surface of sandstone, b) curved and elongated potholes associated with the sedimentary structure, and c) horizontal erosion of multiple potholes that combine to form a large pool-shaped pothole (Choowong et al., 2013).

Figure 1.8 The photo depicts the following features: a) Potholes overlapping in a vertical orientation and merging to form a sinkhole-like cave shape. b) Straight and connected potholes related to a fracture and joint system. c) Potholes occurring in a paleochannel and developing into a canyon (Choowong et al., 2013).

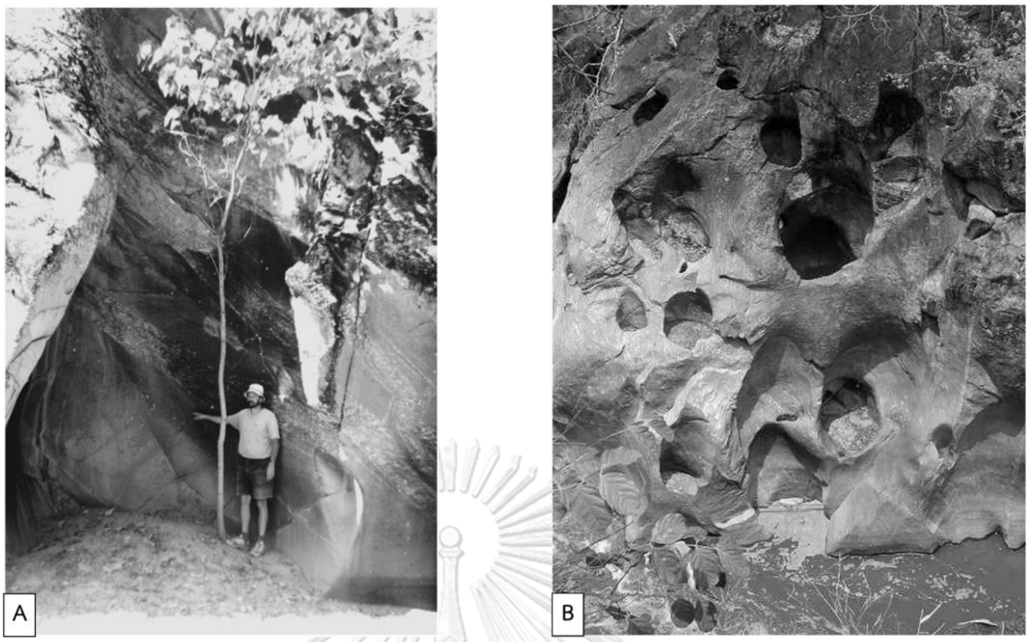


Figure 1.9 An illustration of a pothole found in the Mae Cham River area. (Richardson and Carling, 2005).

1.3 Objectives

The objectives of this dissertation are two-fold. The first goal is to conduct a detailed investigation of the stratigraphy of the Phu Phan Formation and its relationship to the occurrence of potholes and other erosional features. This will involve a comprehensive analysis of the geological characteristics of the Phu Phan Formation and the identification of potential factors that contributed to the formation of potholes and other erosional features.

The second objective is to conduct a thorough analysis of the formation of potholes and other erosional features in the Phu Phan Formation. This will involve the examination of various geological processes and their potential impact on the formation of potholes and other erosional features. Additionally, this analysis will seek to identify any environmental or climatic factors that may have played a role in the formation of these features.

Overall, this thesis aims to provide a comprehensive understanding of the formation of potholes and other erosional features in the Phu Phan Formation. By achieving these objectives, this study will contribute to a better understanding of the geological processes that shape our planet and aid in the development of effective strategies for the management and conservation of geological sites.

CHAPTER 2

LITERATURE REVIEWS

2.1 Lithofacies and Architectural Element

Miall (1985) described that the characteristics of a river, including its sedimentary structure, lithology, and sedimentary composition, are influenced by the size of its grains. This study also categorized lithology and sedimentary structure into lithofacies, which are mesoforms of flow regimes that consist of microforms like ripple marks and occur during dynamic events. Lithofacies are mesoforms of flow regimes. Mesoforms consist of microforms such as ripple marks and occur during dynamic events. Lithofacies are replaced with a facies code, which is related to grain size. In the rock stratigraphy, there are many facies because rivers are migrating all the time, which is called lateral facies change.

An architectural element refers to a specific sedimentary structure or feature within a rock formation, such as grain size, bed form composition, and internal structure. These elements are used to analyze and understand the depositional environment and history of the formation. Accurate measurement of these features in centimeters is important for proper analysis and interpretation. The facies code from Lithofacies can be used to group these architectural elements and provide insight into the paleo-environment of the formation, as detailed in Tables 1 and 2.

Allen (1983) utilized architectural element analysis to study the paleo environment of a river system. This involved identifying and categorizing different sedimentary features resulting from the river's migration, based on their lithology and sedimentary structural characteristics. The architectural elements were further described by analyzing the bed form, grain size, and sedimentary structure, as shown in Figure 2.1. To thoroughly investigate and understand the architectural elements present in the outcrop, a minimum of 10 meters is needed to capture a wide range of facies.

Table 2.1 Lithofacies classification (Miall, 1977b)

Facies code	Lithofacies	Sedimentary structure	Interpretation
Gms	massive, Matrix supported gravel	grading	Debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	Longitudinal bars. Lag deposits, sieve deposits
Gt	gravel, stratified	trough crossbeds	Minor channel fills
Gp	gravel, stratified	planar crossbeds	linguoid bars or deltaic growths from older bar remnants
St	Sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	Sand, medium to v. coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	Sand, very fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	Sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (1. and u. flow regime)
Sl	Sand, fine	low angle (< 10°) crossbeds	scour fills, crevasse splays, antidunes
Se	Erosional scours with intraclasts	crude cross-bedding	scour fills
Ss	Sand, fine to coarse, may be pebbly	broad, shallow scours including eta cross-stratification	scour fills
Fl	Sand, silt, mud	fine lamination, very small ripples	overbank or waning flood deposits
Fsc	Silt, mud	laminated to massive	backswamp deposits
Fcf	mud	massive, with freshwater molluscs	backswamp pond deposits
Fm	Mud, silt	massive, desiccation cracks	overbank or drape deposits
Fr	Silt, mud	rootlets	seatearth
C	Coal, carbonaceous mud	plants, mud films	swamp deposits
P	carbonate	pedogenic features	soil

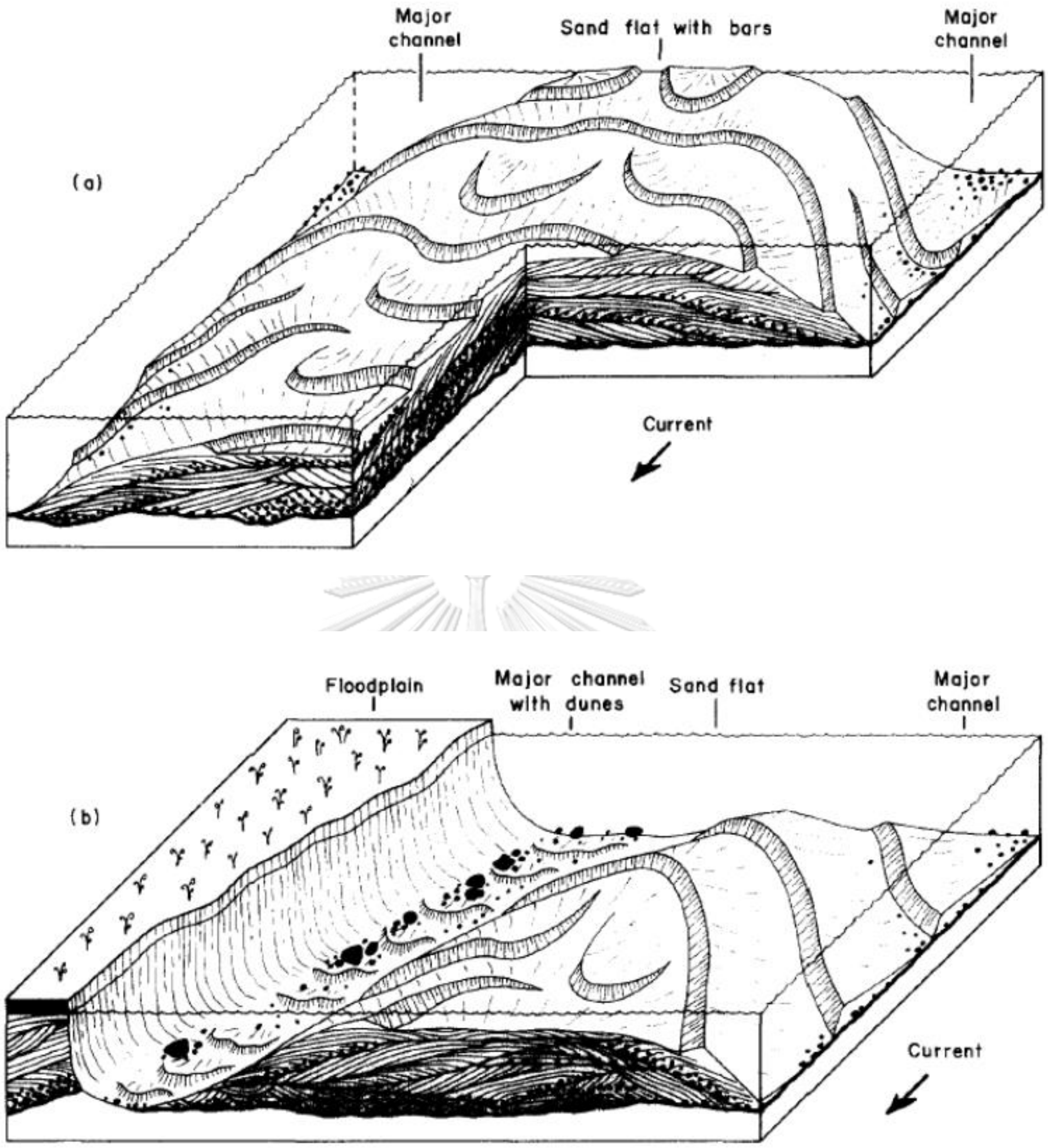


Figure 2.1 Model of river show morphology a) and sedimentary structure from fluvial process and b) river migration (Allen, 1983)

Table 2.2 Architectural element classification in fluvial deposits (Miall, 1985)

Element	Symbol	Principal lithofacies assemblage	Geometry and relationships
Channel	CH	any combination	finger, lens or sheet; concave up erosional base; scale and shape highly variable; internal concave-up secondary erosion surfaces common
Gravel bar and bedforms	GB	Gm, Gp, Gt	lens, blanket; usually tabular bodies; commonly interbedded with SB
Sandy bedforms	SB	St, Sp, Sh, Sl, Sr, Se, Ss	lens, sheet, blanket, wedge; occurs as channel fills, crevasses splays, minor bars
Foreset macroforms	FM	St, Sp, Sh, Sl, Sr, Se, Ss	lens resting on flat or channeled base, with convex-up second-order internal erosion surfaces and upper bounding surface
Lateral accretion deposits	LA	St, Sp, Sh, Sl, Sr, Se, Ss ; less commonly Gm, Gt, Gp	wedge, sheet, lobe; characterized by internal lateral accretion surfaces
Sediment gravity flows	SG	Gm, Gms	lobe, sheet; typically interbedded with GB
Laminated sand sheets	LS	Sh, Sl ; minor St, Sp, Sr	sheet, blanket
Overbank fines	OF	Fm, Fl	thin to thick blankets; commonly interbedded with SB; may fill abandoned channels

2.2 Paleo-current and Stratigraphy of Khorat Formations

The river system has many flow directions, but it has only one main flow direction. The two most common indicators used for pointing out paleo-currents are planar cross-lamination and trough cross-lamination. Furthermore, the orientation of the channel, imbrication of conglomerate, and cross bedding of sandstone also indicate the flow direction of the paleo-current, e.g., a braided river (Miall, 1977b). The study of paleo-current in sandstone is to collect the data of paleo-current from the dip direction of cross-lamination and plot them in a rose diagram (Trexler and Cashman, 1990). Horiuchi et al. (2012) studied the river system from stratigraphy and paleosol along Road No. 210 in Nong Bua Lamphu province. They used lithofacies classification and architectural elements to classify stratigraphy and analyzed characteristics of rivers in the Phu Kradung Formation, Phra Wihan Formation, and Sao Khua Formation in the Khorat Group (Figure 2.2).

Chenrai (2011) analyzed the paleo-current of the Sao Khua Formation, Khorat Group, and Nong Bua Lamphu, northeast of Thailand, which exposes along Highway No. 201. Sedimentary structures such as cross bedding and ripple marks were used to identify paleocurrent directions. Paleo-current data in this area are corrected by measuring the dip angle and dip direction of cross strata. The mean direction of paleo-current from 158 pieces of data was plotted into a stereo net, and the result shows that the flow direction is in the NE direction. However, the flow direction differs from Racey (2009), who shows that the paleocurrents of the Sao Khua Formation are from the west and southwest due to the change in flow direction from location to location. Chenrai (2011) concluded that the paleoenvironment of the Sao Khua Formation in the Nong Bua Lampu region is a braided river because of its smaller range of directions.

Horiuchi et al. (2012) analyzed the paleocurrent of the Phu Kradung Formation, Phra Wihan Formation, and Sao Khua Formation in the Khorat Group at Nong Bua Lampu Province. They collected data from cross-bedding structures and applied the rose diagram to analyze paleocurrents. They concluded that the paleo-environment of these formations is an anastomosing river system with semi-arid weather and a direction of paleo-current flow from the northeast to the southwest (Figure 2.3).

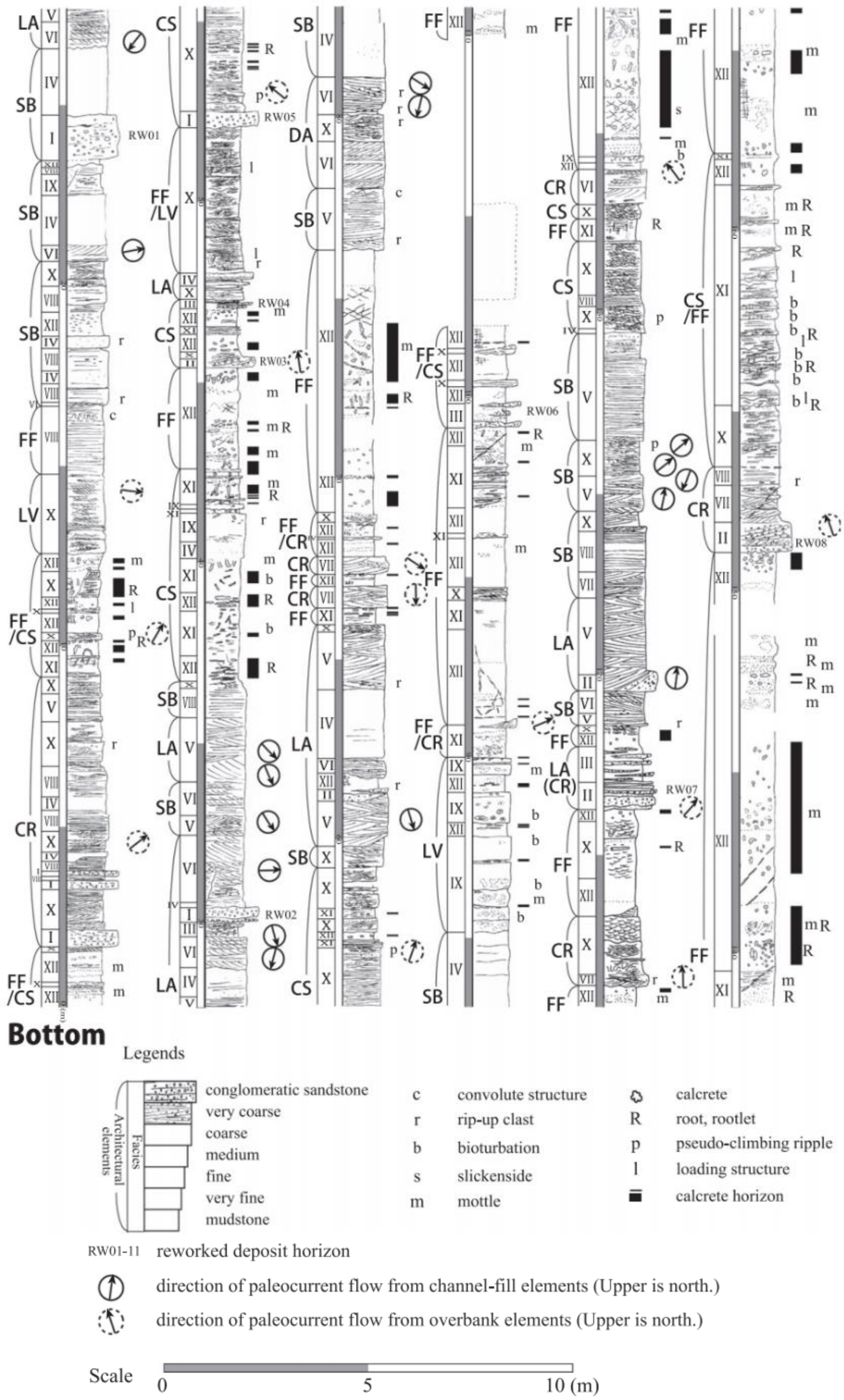


Figure 2.2 Detailed stratigraphy of Phu Kradung Formation, Phra Wihan Formation and Sao Khua Formation in the Khorat Group facies and their architectural elements (Horiuchi et al., 2012).

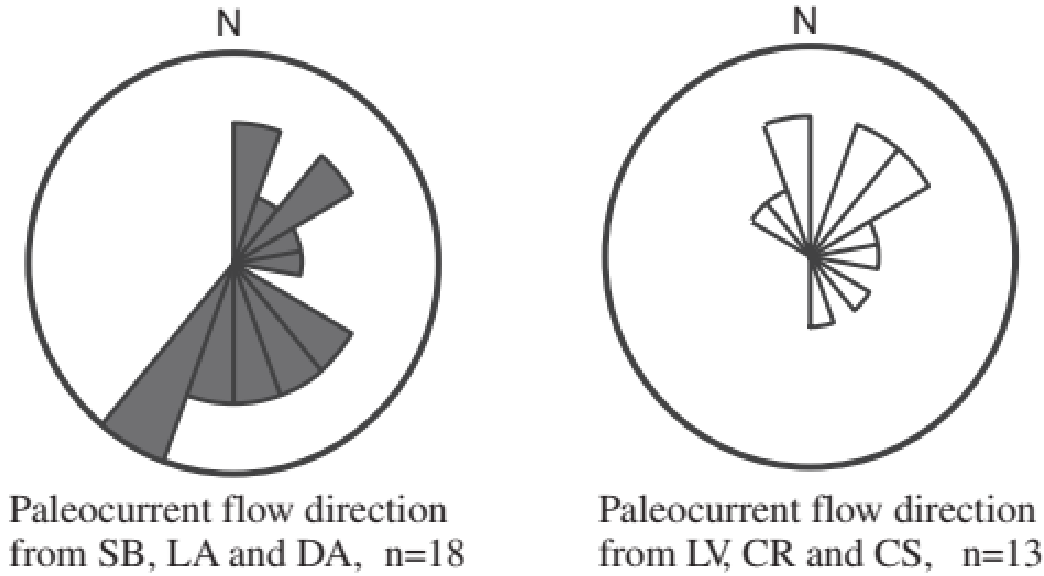


Figure 2.3 Paleocurrent flow directions for Nong Bua Lampu Province. In the pictures, n are the data of paleocurrent that plot in rose diagram. (Horiuchi et al., 2012).

2.3 Pothole Formation and Sedimentary Process

Potholes are typically observed in riverbeds, glaciers, and waterfall beds. They are characterized as cylindrical holes bored into bedrock beneath a glacier, caused either by water falling through a deep moulin or by rotating boulders in the bed of a meltwater stream (Alexander, 1932). As water and sediment flow through the bedrocks, the sediment transported by the water grinds against the bedrocks, leading to the formation of potholes (Figure 2.4). Bedrocks consisting of fractures or joints are more susceptible to erosion by potholes. (Choowong, 2011).

The origin of potholes can be traced back to Alexander (1932) research. Potholes are formed by the grinding action of stones, sand, and sediment transported by the current on the channel bed. They can occur in homogeneous igneous, sedimentary, and metamorphic rocks, and their shapes are influenced by the angle and position of the currents that flow into them (Figure 2.5).

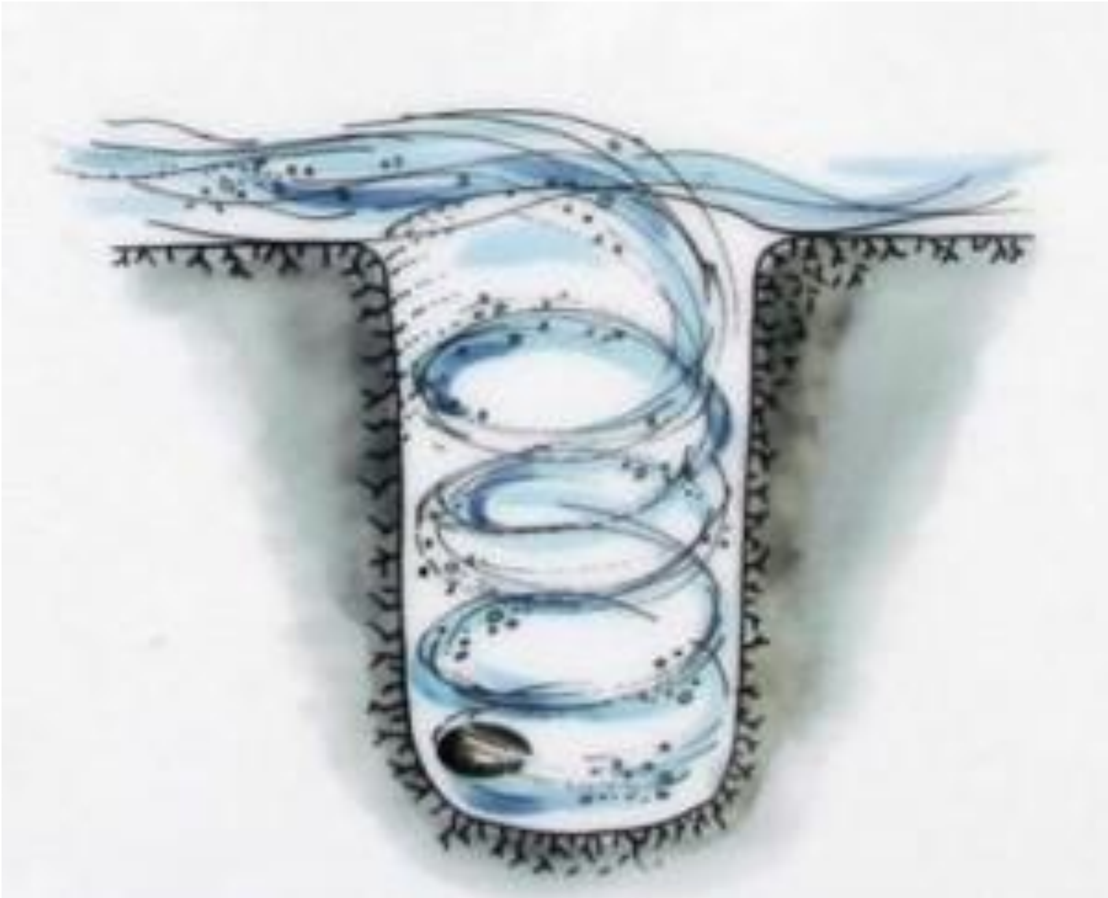


Figure 2.4 A sketch can illustrate the process of boulder grinding in bedrock, which leads to the formation of a pothole. (http://grandma-in-lapland.com/the-largest-devils-churns-of-finland-you-find-in-lapland/)

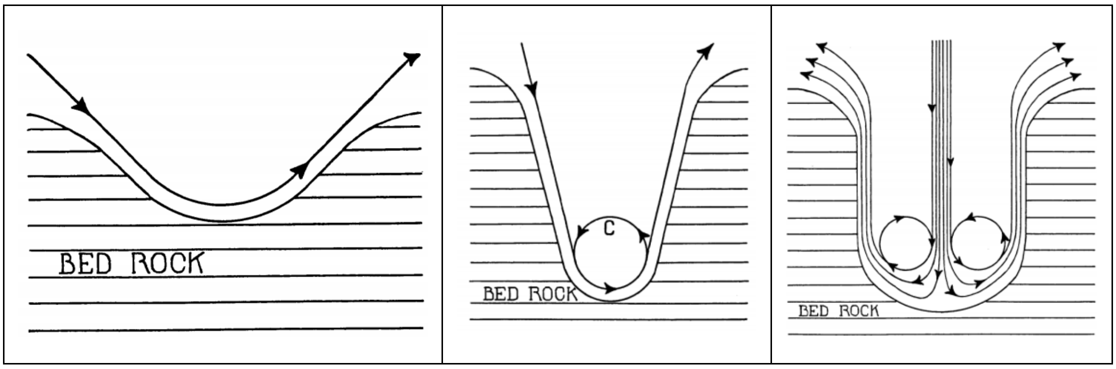


Figure 2.5 The shape of a pothole can vary depending on the angle of the current that formed it. (Alexander, 1932).

The formation and preservation of potholes are mostly recognized in sandstone. The updated work by Fleming and Brand (2019) exposed the wind-induced pothole erosion in Nojavo sandstone at Rock Window Mesa in the Chinle Valley of Arizona, United States. Ji et al. (2019) also mentioned the pothole erosion from sandstone in the Sunxi River, China. Ji et al. (2019) measured the average aperture aspect ratio of potholes and the mean diameter to depth of a pothole. As a result, they concluded that the stream pothole is deepening faster than it is widening and that the orientation of the pothole's aperture is related to stream flow. If the mean diameter to depth ratio of a pothole is 1.0 ± 0.2, the pothole will trap coarser sediment, making it easier to grind the bedrock in the pothole.

The classification and relationship between diameter and depth of potholes eroded by running water were reviewed (Ji et al., 2018). Potholes were classified into three types: 1) stream potholes, which occur in a stream or river; 2) marine potholes, which occur on the shore in beach rock that erode by wave; and 3) hillside potholes, which occur on a hillside and erode by rainwater flow on the slope of a mountain. Ji et al. (2018) applied parameters a, b, a/b, D, h and D/h for pothole classification. Parameters a and b are major axis, minor axis of aperture and ratio between this axis, respectively. D, h and D/h are mean diameter ($D = \sqrt{ab}$), depth of potholes, and pothole depth – diameter relationship, respectively. Marine and hillside potholes a/b are close to 1 more than stream potholes, which means the apertures of marine and hillside potholes are circular. Potholes depth-diameter relationship can be calculated using a linear equation.

$$D = Nh+m. \qquad \text{Eq. (2.1)}$$

N is the slope of the straight line of h-D plotted. N is the relative ratio of potholes widening to deepening, and m is the critical size of the original concavities (seminal potholes) that subsequently underwent growth. If the aperture of potholes is smaller than m, it cannot trap grinder in the pothole, but if the aperture of potholes is larger than m, these potholes can generate strong eddies current and the highest rate of erosion. The value of m varies with the type of rock. In stream potholes, parameter N is commonly about 0.67, which means stream potholes are deepening faster than widening. In marine and hillside potholes, the N values are 1.53 and 2.02, respectively, from data for Oahu Island, Hawaii, and Mt. Jefferson, White Mountains, New Hampshire, USA, which means they are widening faster than they are deepening. Diameter to depth ratio indicates the rate of erosion between the wall and the bottom of the pothole Marine potholes and hillside potholes have D/h = 2.04 while stream potholes have D/h close to 1. These indicate rivers have a higher potential to erode bedrock than waves or rainwater. Rainwater can only transport small-sized sediment (sand), and waves can transport small- to medium-sized sediment (sand, pebbles, and cobbles), but a stream can transport large-sized sediment, such as pebbles, cobbles, and boulders, by flooding. Small size sediment can suspend in water and erode walls of potholes easier than large size sediment that rolls and slides at the bottom by the effect of gravity.

Potholes are classified by Choowong et al. (2013) into two types: those that are controlled by fracture and those that are not controlled by fracture. In the first group, the pothole was eroded into a fracture or joint and took on an oval shape. The potholes that occur in fractures are continually made larger. After that, it will connect and develop into a coalesced pothole (Choowong et al., 2013). The second group is non-structured and uncontrolled. Richardson and Carling (2005) studied how potholes form when vortex flow or eddy currents erode depressions in the bedrock or side walls of a channel. Non-structure-controlled potholes can be divided into five groups: simple potholes, potholes with external furrows, compound potholes, breached potholes, and lateral potholes (Figure 2.6). First, simple potholes are uncomplicated potholes, and they are deficient in secondary sculpture. Second, potholes with external furrows are the potholes that erode to a furrow on the rim at one or more points in different degrees, and they may show the recent flow direction. Third, compound potholes are the potholes that have the secondary sculpture, which is the small-scale pothole, inside the potholes. Fourth, breached potholes are those that erode slowly until they are picked off the wall. Breached potholes usually occur near the channel's steep margin. The last one, lateral potholes, are the potholes that erode on the side walls of the channel.

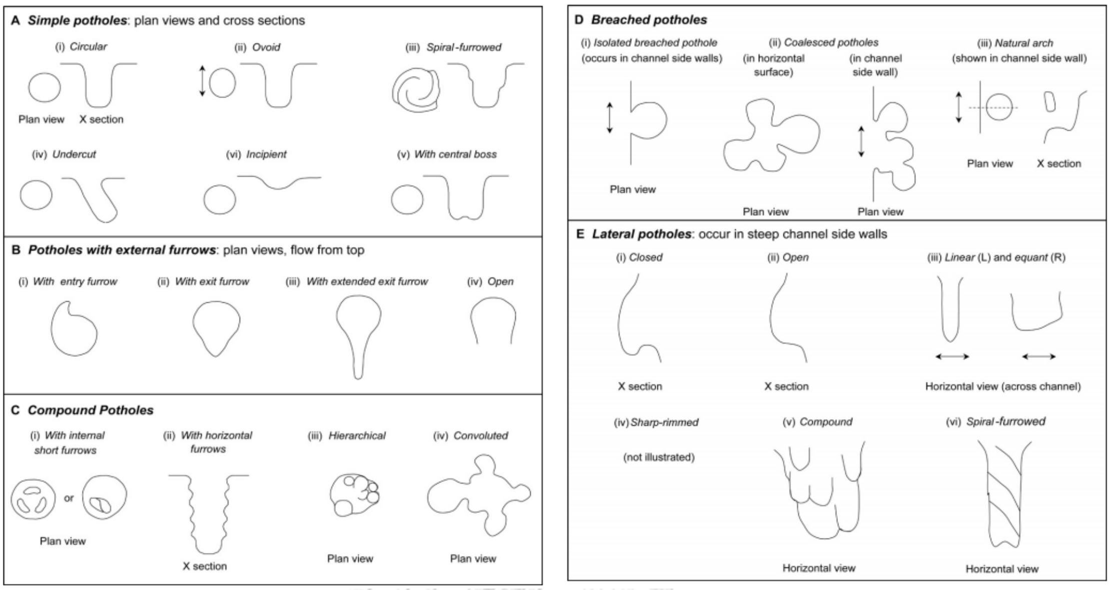


Figure 2.6 Non-structure-controlled potholes can be classified according to the system proposed by Richardson and Carling (2005) base on size, shape, and location of potholes forming.

2.4 Giant Pedestal Rock

A giant pedestal is a rock mass that has been eroded to rest on a smaller base or residual rock (Nocita, 1986). This distinct geological feature is a result of differential weathering and erosion, which forms pedestal rocks. Although pedestal rocks are often found in shale base rock, they can also occur in most types of sedimentary rock, and are typically found in arid climates, where wind erosion is prominent. The cap rock of pedestal rock is either conglomerate or shale (Blackwelder, 1909).

The formation of rock mushrooms study by Duszyński and Migoń (2022) is influenced by three main geological controls. The first control is the relationship to rock layering, with a more resistant layer supporting the cap. The second control involves random distribution of resistant elements, often seen in glacigenic deposits. The third control includes rock mushrooms not showing clear rock-related influences, primarily originating from increased rock disintegration in the lower part of the outcrop. These controls contribute to the diverse formations observed in rock mushrooms, highlighting the importance of rock layering, random distribution, and localized disintegration processes in their creation (Figure 2.7).

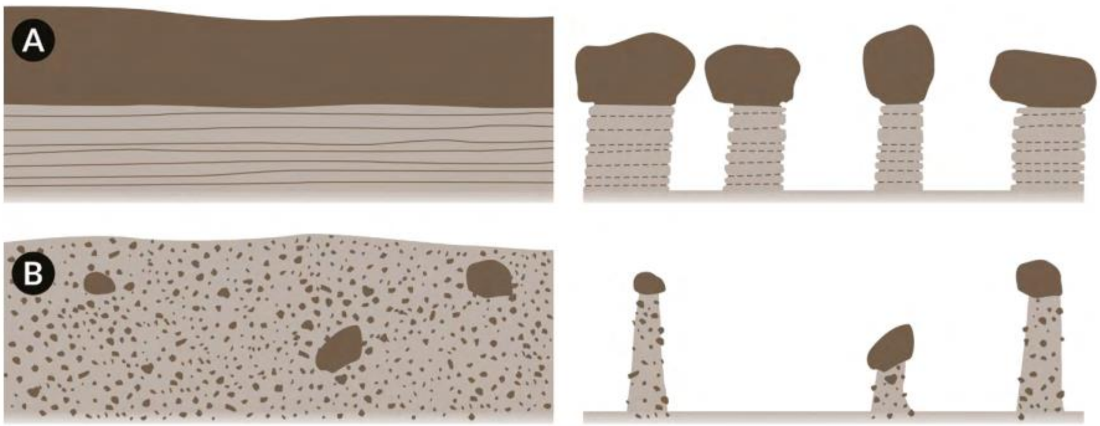


Figure 2.7 The picture show the process of pedestal rock formation. A) pedestal rock formation in overlay resistance bed rock. B) random of resistance rock forming the pedestal rock (Duszyński and Migoń, 2022).

Duszyński and Migoń (2022) also study about the origin of the pedestal rock. Rock mushrooms can have multiple origins, and many of them are actually polygenetic, meaning they result from various processes. However, it is clear that rock disintegration is most efficient in the lower part of the mushrooms. The reasons for this enhanced efficacy can vary. One reason is aeolian undercutting, which is commonly taught in geography education, although wind-abraded rock mushrooms are not the most common examples. Another reason is differential weathering, which is influenced by variations in rock composition or structure. The exact mechanisms of weathering can differ. Subsurface weathering or etching can also contribute to the formation of rock mushrooms, where a narrow stem is created and later exposed. In coastal areas, wave-undercutting plays a role. Overland flow and gully erosion are fundamental processes in the evolution of rock mushrooms in loosely consolidated deposits. Additionally, there can be a negative feedback relationship between stress and erosion on exposed bedrock outcrops.

The Yehliu Geopark, the pedestal rock was formed by water becoming trapped in the undulating surface caused by wave erosion. As the water dries out and the process is repeated, the weathering layer becomes a cap rock, and more weathering occurs around the surface of the pedestal rock than on the cap rock (Figure 2.8) (Hong and Huang, 2001).

On the other hand, the research conducted by Bryan (1926) suggests that wind is not the primary factor in the weathering and erosion of shale, indicating that the process of pedestal rock formation cannot be attributed to a single mechanism. Indeed, the formation of pedestal rock is complex and multifaceted, involving a range of processes (Cramer, 1963; Laity, 2014).

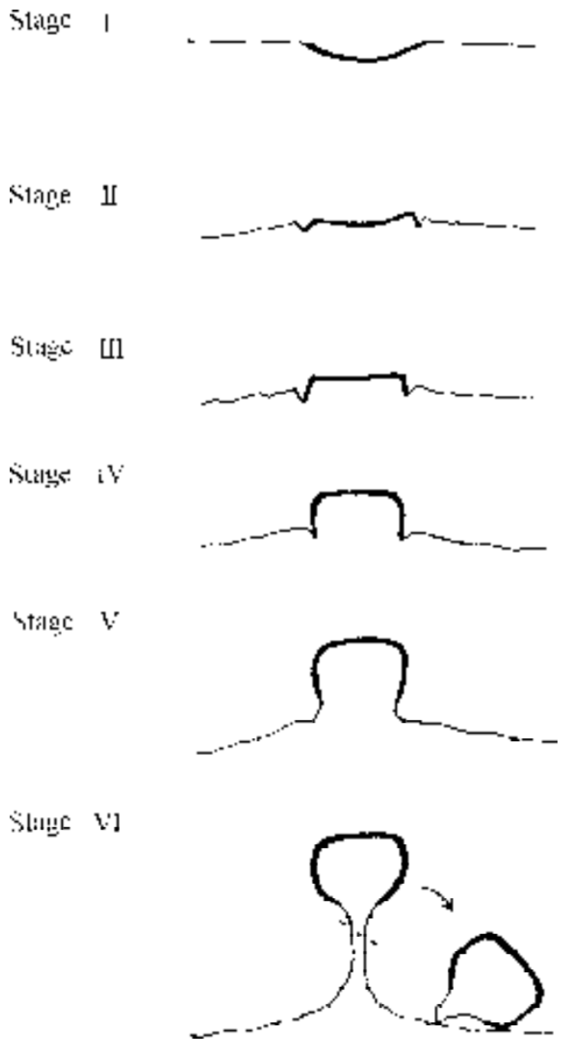


Figure 2.8 The process of pedestal rock formation at Yehliu Geopark, located on the northern coast of Taiwan (Hong and Huang, 2001)

CHAPTER 3
METHODOLOGY

The methodology used in this study to investigate the typology and formation of potholes and erosional remnants in sandstone of the Khorat group is divided into four main steps.

The first step is thesis preparation, which includes conducting a literature review to identify the relevant background information and previous research on the subject. Additionally, the geological setting of the study area is evaluated to understand the context in which the potholes and erosional remnants are formed.

The second step involves remote sensing interpretation, which includes using satellite images to identify potential study areas with potholes and erosional remnants.

The third step is field investigation, which involves classifying the types of potholes and erosional remnants, collecting data through various methods such as drilling and using drones for mapping. The collected data includes information about the size and shape of the potholes, as well as the sediment and pebbles found within the sandstone bed.

The fourth step is to analyze the data collected from the field investigation. Grain size analysis and counting the percentage of pebbles within the sandstone bed are performed. Additionally, an erosional model of the pothole and giant pedestal rock formation is built to better understand their formation mechanisms.

The final step is the discussion and conclusion, where the findings of the study are presented, and the implications of the results are discussed in detail.

1. Thesis preparation

- The literature review
- The geological setting of the study area
- The previous research

↓

2. Remote Sensing Interpretation

↓

3. Field Investigation

- Classify type of pothole
- Data collection
- Collecting grinder inside pothole
- Drone mapping

↓

4. Analyze Data from the Field

- Grain size analysis
- Counting the percentage of pebbles inside the sandstone bed
- Building the erosional model of the pothole and giant pedestal rock formation

↓

5. Discussion and Conclusion

Figure 3.1 The methodology used in this study is comprised of four main steps, as illustrated in a simplified flow chart.

3.1 Thesis Preparation

The first step in this methodology is the Thesis Preparation, which consists of three subsections: the literature review, the geological setting of the study area, and previous research related to potholes, pedestal rock erosion, and the Khorat Group sandstone stratigraphy. The primary objective of this step is to gain an in-depth understanding of the erosional processes involved in pothole and pedestal rock formation, as well as the classification of fluvial erosional processes. Additionally, this section aims to investigate the stratigraphy of Khorat Group sandstone in northeastern Thailand, including its ages, paleo environmental conditions, and tectonic evolution. By reviewing the existing literature and analyzing the geological setting of the study area, this methodology aims to provide a comprehensive understanding of the factors contributing to the formation and evolution of potholes and erosional remnants in sandstone.

3.2 Remote Sensing Interpretation

Remote Sensing Interpretation (RSI) is a technique that utilizes remote sensing data, such as satellite imagery, to study the geology and geomorphology of a given study area. The primary objective of this technique is to obtain a comprehensive understanding of the terrain and geological structures that define the landscape.

In RSI, a geological map is used to identify the rock formations and geological structures of the area. This is followed by the creation of an elevation map using a Digital Elevation Model (DEM) with a resolution of 30 meters. The elevation map is used to determine the geological structure and geomorphological features of the study area. This includes identifying the location of hills, valleys, and other terrain features.

Figure 3.2 shows the use of RSI to observe decadal changes in riverbank position using a satellite image derived from LANDSAT TM5 satellite imagery captured between 1999 and 2006, along with a Google Earth image from 2009. The riverbank position in this area changes as water levels fluctuate throughout the seasons. The analysis of this data enables researchers to identify any changes in the position of the riverbank over time.

Furthermore, Google Earth images were enhanced to help locate potholes, a paleo channel, and a canyon at Samphunbok. These features provide valuable information about the geological history of the region and help researchers to understand the processes that have shaped the landscape over time.

In conclusion, RSI is a powerful tool that enables researchers to gain a comprehensive understanding of the geology and geomorphology of a study area. By utilizing remote sensing data, researchers can study changes in the landscape over time, identify geological structures, and gain insight into the history of the terrain.

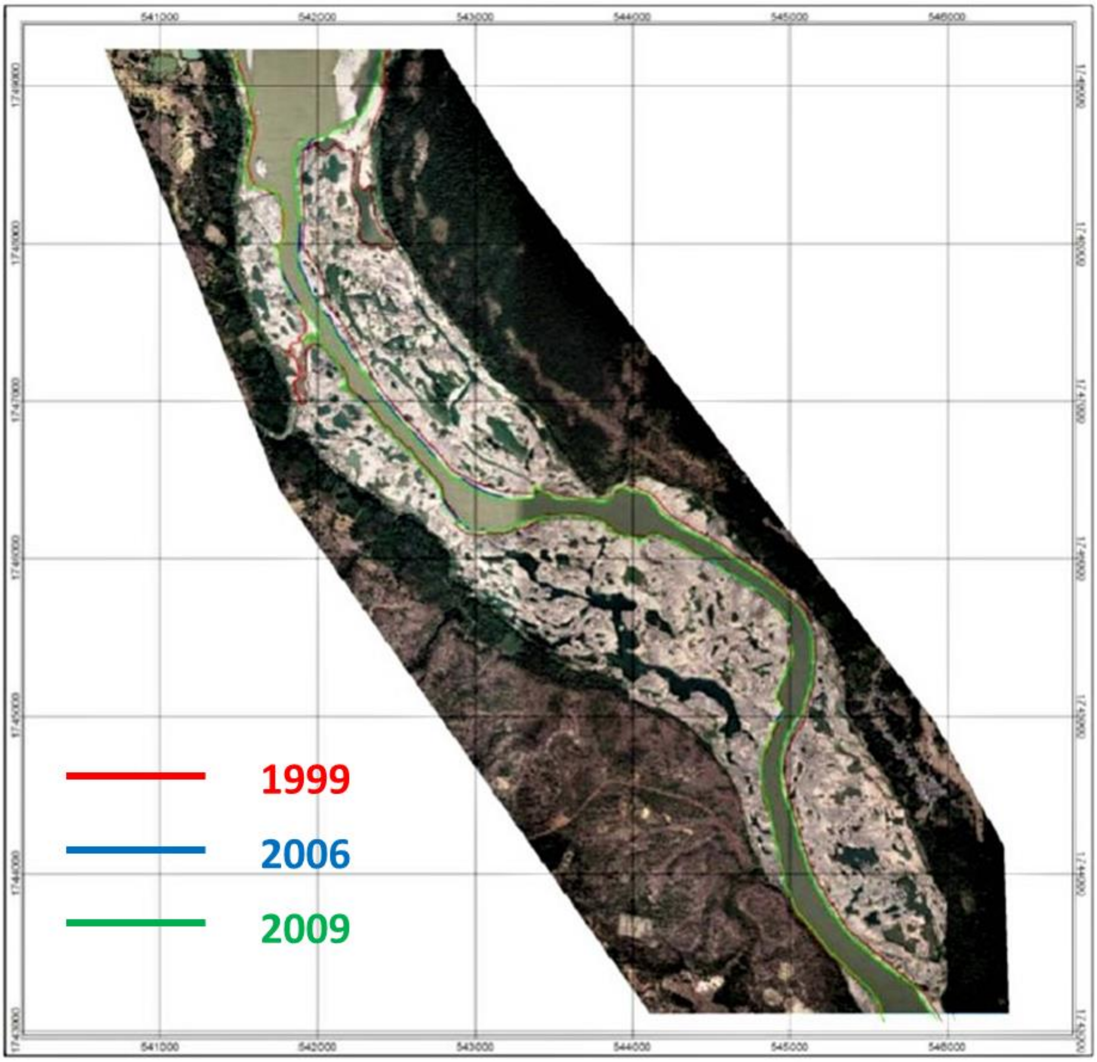


Figure 3.2 The decadal changes in the position of the riverbank were assessed by utilizing remote sensing data obtained from a LANDSAT TM5 satellite image between 1999 and 2006 and a Google Earth image captured in 2009.

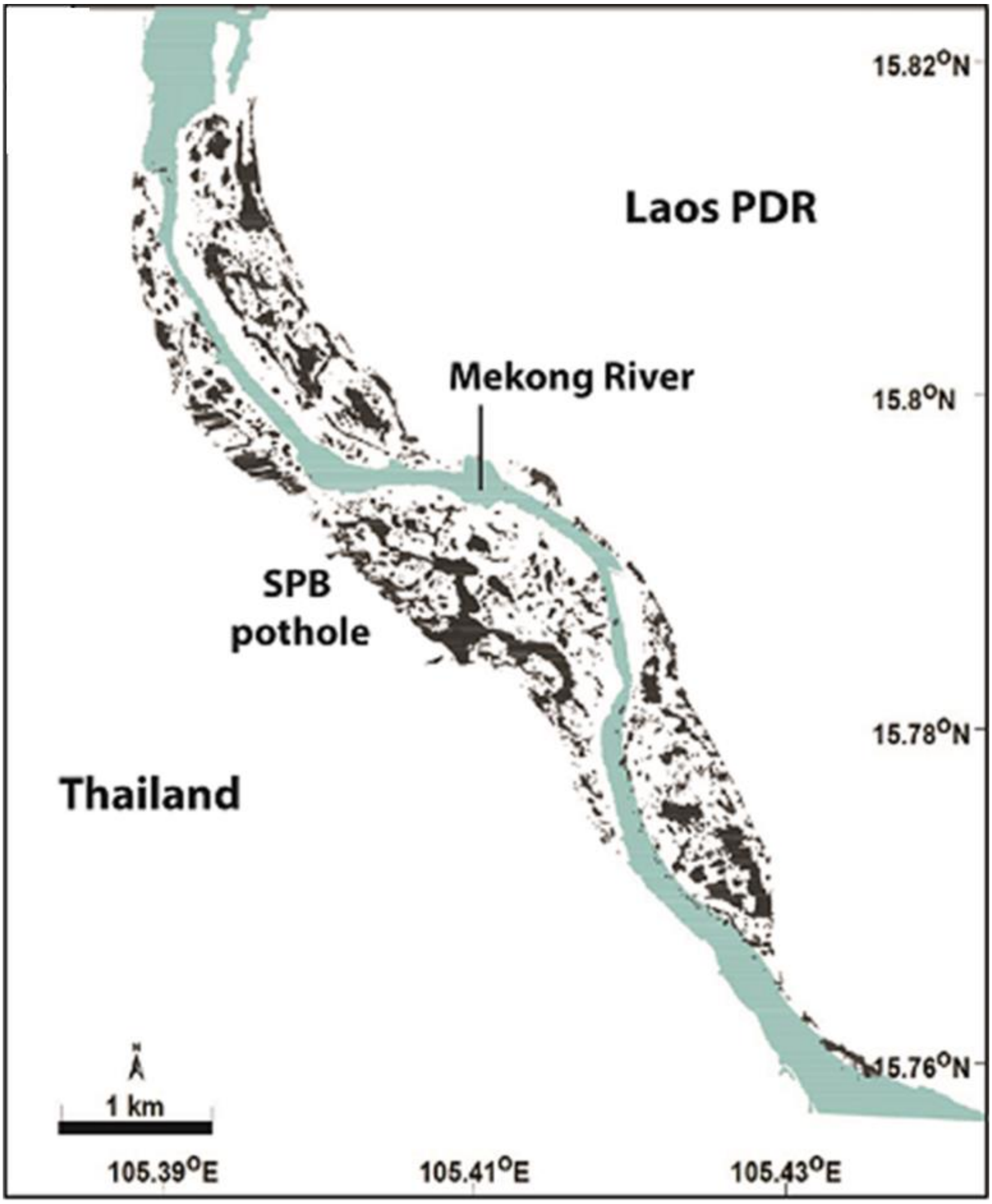


Figure 3.3 Image processing techniques were applied to enhance Google Earth images, which aided in the identification and mapping of geological features such as potholes, a paleo channel, and a canyon at Samphunbok (SPB).

3.3 Field Investigation

3.3.1 Classify Type of Pothole

The process of classifying potholes involved the measurement of their size and shape in centimeters (Figure 3.4). Additionally, the location and density of the potholes were taken into account to determine the factors contributing to their occurrence. The geological structures, including fractures and joints, were also considered in identifying the type of pothole. The study also examined the elevation of pothole occurrences as part of the discussion on erosion caused by fluvial processes. This comprehensive approach allowed for a better understanding of the different types of potholes and the underlying factors contributing to their formation. By identifying the specific characteristics of each pothole type, researchers can gain insight into the various environmental conditions that can lead to their formation.

3.3.2 Data Collection

During data collection, the lithology of the Sao Khua and Phu Phan Formations was examined to create a stratigraphic column of the pothole formation and pedestal rock. Additionally, sedimentary structures, such as trough-crossbedding and planar-crossbedding (as depicted in Figure 3.5), were also recorded. The rock bedding was measured to determine the occurrence of potholes. Furthermore, the lithology and sedimentary structure data were utilized to identify the paleocurrent and paleo environment of the Sao Khua and Phu Phan Formations. This comprehensive data collection approach enabled a better understanding of the geology of the study area, including the factors that contributed to the formation and development of the potholes. The collected data were then used for further analysis and interpretation to generate meaningful insights into the study area's geology and geomorphology.

Figure 3.4 The image depicts the process of measuring the size and shape of a pothole.

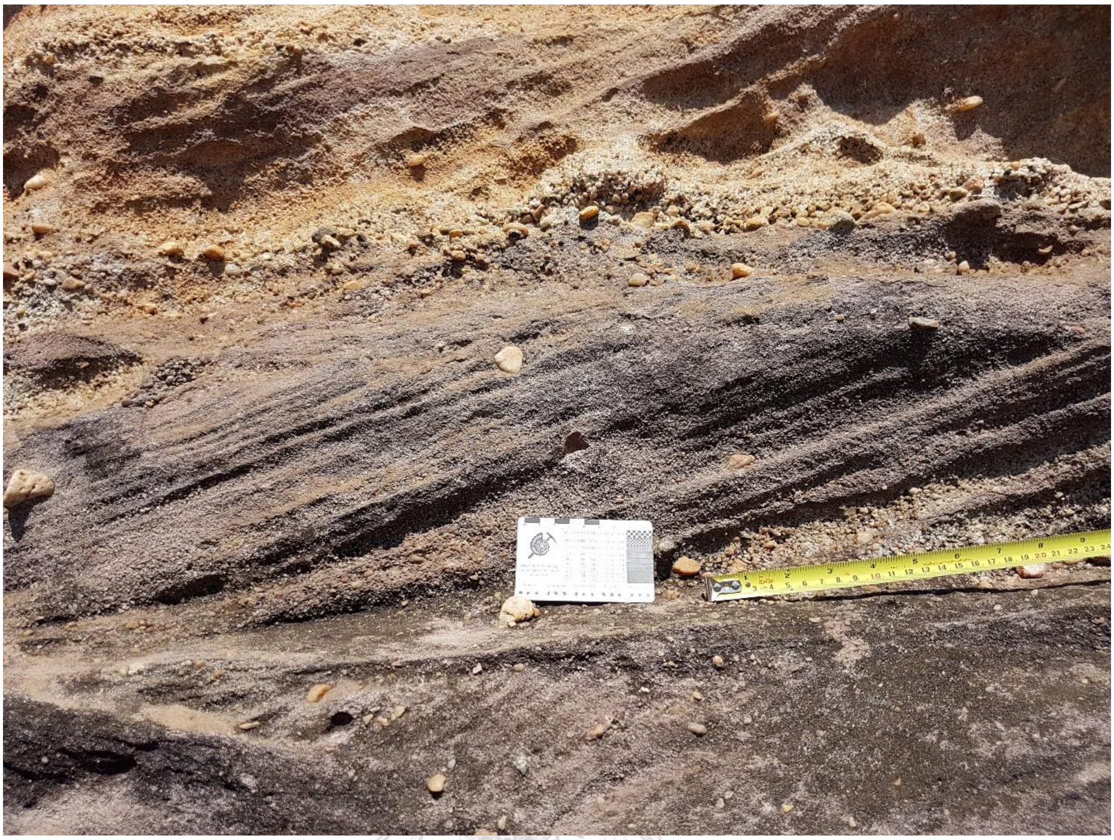


Figure 3.5 The example of planar cross-bedding in Phu Phan formation sandstone.

3.3.3 Collecting Grinder inside the Pothole

To understand the process of differential pothole erosion, the sediments inside the potholes were collected and analyzed. These sediments, which include sand, pebbles, and granules, are known as "grinders" (Figure 3.6). Around 25 samples of grinders were collected from each elevation to determine the origin of these sediments. By studying the grinders inside the potholes, researchers can gain insights into the factors that contribute to differential erosion and the overall evolution of the landscape. This information can be used to develop more effective conservation and management strategies for these unique geological features.

Figure 3.6 The image displaying various sizes of grinders found inside the pothole.

3.3.4 Drone Mapping

Drone mapping has revolutionized the field of geology and has become an important tool in studying geological formations. In the Samphunbok area, a five square kilometer region, there are numerous potholes that need to be studied. To achieve this, a DJI Mini 3 Pro drone was flown in a grid pattern and captured aerial photographs with a resolution of 48 megapixels (Figure 3.7). The drone was flown at an altitude of 90 meters, following the laws set by The Civil Aviation Authority of Thailand for operating UAVs.

To capture detailed photographs, the camera of the drone was tilted around 10-20 degrees from the vertical, enabling it to capture the depth of the potholes and their elevation in the canyon (Figure 3.8). It's important to note that the camera should be tilted less than 3 degrees in the vertical plane, but it can be tilted more than 3 degrees to capture detail in the horizontal plane. The drone was flown in a grid pattern over the Samphunbok area where the 1949 photo was taken.

To create a map view photo, the drone's pathway must be close enough to take a 60% overlap photo at least. The Agisoft Metashape program was used to combine the 1949 photo of Samphunbok. The program detected the same point in each photo and aligned them into the correct position using the same point and UTM coordinates. If the aligned photo does not have enough of the same point, the program can generate dense cloud points to build texture in the next step. Texture was then put into the model that was generated by the same point and dense cloud. After that, DEM (Digital Elevation Model) and orthophoto (an aerial photograph corrected to remove distortion) were built from the point cloud and UTM coordinates.

Finally, the map view photo was used to locate the location and density of potholes. The location and density of potholes were used to find the morphological factor of pothole occurrence. By using drone mapping, it was possible to capture detailed photographs of the potholes and create accurate maps, which can be used to study their morphology and formation. This information can provide valuable insights into geological processes and aid in future studies of geological formations.

Figure 3.7 The image displays the grid pattern pathway followed by the drone to capture photos with a minimum of 60% overlap.

Figure 3.8 The example of the photo from drone to locate the location and density of potholes.

3.4 Analyze Data from the Field

3.4.1 Grain Size Analysis

To assess and compare the volume and size of grinders inside potholes from various elevations and locations, a grain size analysis was conducted. Samples were collected from each pothole situated at different elevations to represent the type of pothole and the lithology of the pothole formation stratigraphic column. To identify the sediment size and separate the mixed sediments, a sieve mesh number of 5, 10, 18, 35, 60, 120, 230, and a pan were employed. The sediment size was classified into pebble, granule, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, and silt according to the Wentworth scale (as shown in Figure 3.9). The volume of each sediment size was then calculated to compare the pebbles inside the sandstone bed.

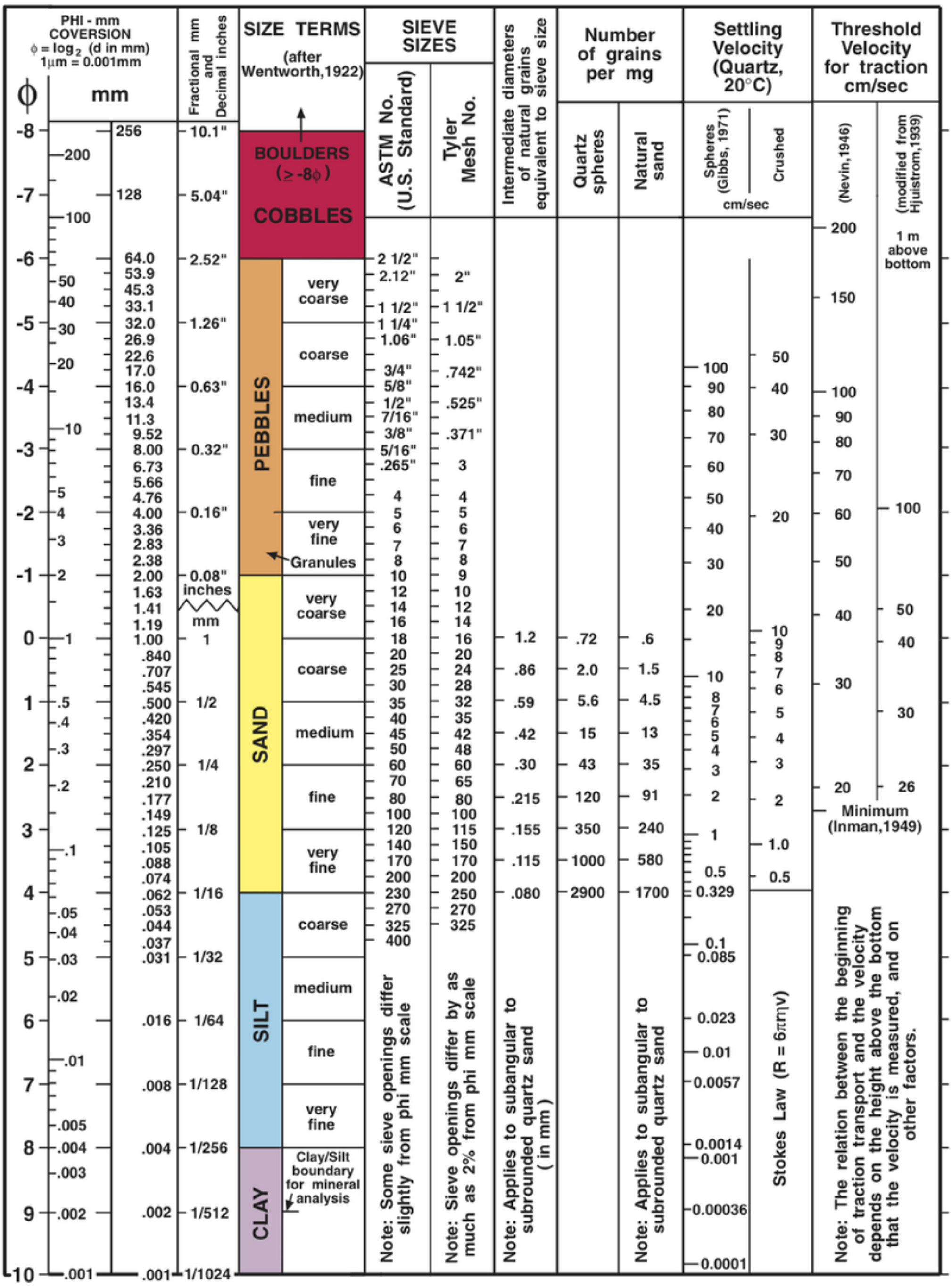


Figure 3.9 The picture show the sediment size from Wentworth scale and the sieve number that use to separate the sediment size.
(https://en.wikipedia.org/wiki/Grain_size#/media/File:Wentworth_scale.png)

3.4.2 Counting the Percentage of Pebbles inside the Sandstone Bed

The sandstone of the Phu Phan Formation is composed of pebbly sandstone, with sand, granules, and pebbles constituting the sediment inside the pothole. The pebbles within the sandstone beds were tallied in both the horizontal and vertical planes (Figure 3.10). The location for counting the pebbles was chosen from the sandstone bed associated with pothole formation, which represented the Samphunbok stratigraphic column. A photo of the pebbles within the sandstone bed was captured in both the vertical and horizontal directions. The composition of the pebbles inside the sandstone bed was determined using a comparison to estimate composition (Lindholm, 1987) (Figure 3.11). The number of pebbles was then utilized to compare the grinders within the potholes and the density of potholes in various sandstone beds.

Figure 3.10 The photograph depicts the process of counting pebbles in a horizontal plane within the sandstone bed.

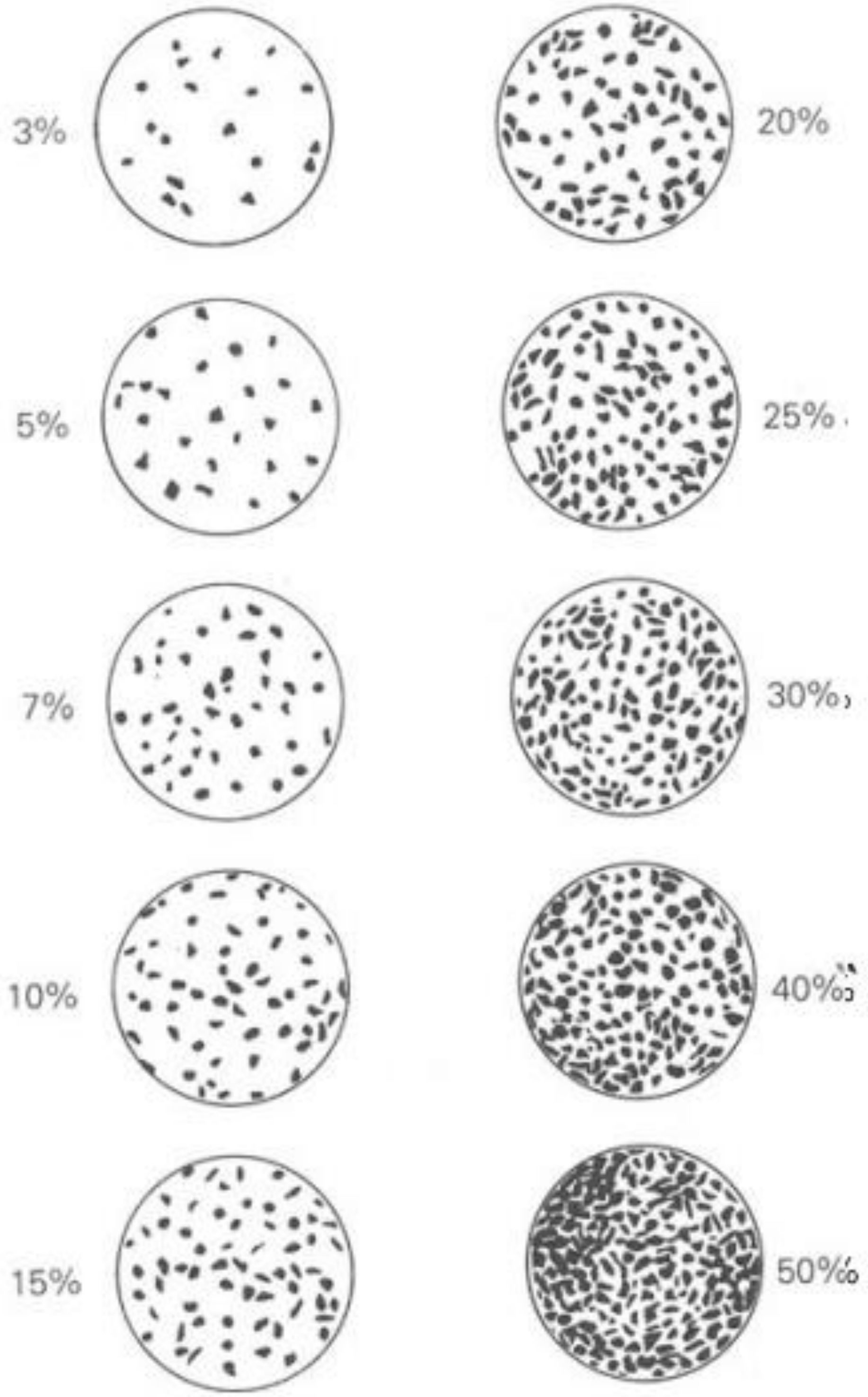


Figure 3.11 A chart for comparing and estimating the composition of sandstone (Lindholm, 1987).

3.4.3 Building the Erosional Model of the Pothole and Giant Pedestal Rock Formation

In order to create an accurate model of the evolution of pothole occurrence and the formation of giant pedestal rocks in the Samphunbok region, data from various sources were used. These sources include lithology, sedimentary structure, regional geology, tectonic evolution, and geomorphology. By integrating these data sources, it was possible to build a comprehensive erosion model of the area. The lithology and sedimentary structure data were used to determine the type of rock formations present in the Samphunbok region, as well as the sedimentary processes that occurred during their formation. The regional geology data provided information on the geological history of the area, including the types of rocks and sediments that have been deposited over time. The tectonic evolution data was used to understand the impact of tectonic activity on the formation of the landforms in the region. Finally, the geomorphology data was used to study the surface features of the area and the processes that shaped them.

Using these data sources, an erosion model was developed that explains the formation of potholes and giant pedestal rocks in the Samphunbok region. The model suggests that the potholes were formed through a process of abrasion caused by water and sediment erosion, combined with chemical weathering. This process created circular depressions in the sandstone and conglomerate bedrock. Over time, the erosion process caused the formation of giant pedestal rocks, which are characterized by their isolated position above the surrounding landscape. The differential erosion of the surrounding rock, leaving a remnant of the harder, more resistant rock on top, forms the pedestal rocks. This process is known as differential weathering.

The model also suggests that the tectonic activity in the area has played a role in the formation of the potholes and pedestal rocks. The region has experienced several periods of tectonic uplift and subsidence, which have caused changes in the local drainage patterns and sediment deposition. These changes have influenced the erosion and weathering processes that have shaped the landscape over time.

In summary, the erosion model developed for the Samphunbok region integrates data from various sources to provide a comprehensive understanding of the formation of potholes and giant pedestal rocks in the area. This model has the potential to aid in the study of similar landforms in other regions and can be used to develop a better understanding of the geological processes that shape our planet's surface.

3.5 Discussion and Conclusion

The study provides an in-depth analysis of the evolution of pothole and pedestal rock formations in the Samphunbok region. Through the utilization of various geological data such as lithology, sedimentary structure, regional geology, tectonic evolution, and geomorphology, the study has developed an erosional model for the formations.

The section also highlights the importance of understanding paleo environments and paleo currents in the formation of such geological structures. The discussion on paleo environments and paleo currents sets the foundation for Chapter 5, which delves deeper into the topic.

Overall, the study has provided valuable insights into the formation and evolution of pothole and pedestal rock formations. The detailed results and discussion will be presented in Chapter 6.

CHAPTER 4
RESULT

The research findings presented in this study have been obtained through a combination of field investigations and laboratory testing, which were conducted in accordance with the methodology outlined in Chapter 3. The data collected from these methods have enabled the study of various aspects of the study area, including the prominent geological and geomorphological features. Additionally, the study of pebble counting has allowed for an investigation into the occurrence of potholes, which is a key area of interest. The study of stratigraphy, lithofacies, and architectural elements, along with the analysis of paleocurrent and paleoenvironment, have provided a comprehensive understanding of the geological history and evolution of the study area. Overall, this chapter is an essential component of the study, providing a detailed account of the methods used and the results obtained.

4.1 Prominent Geological and Geomorphological Features

After conducting field surveys, it was found that the lowest sandstone bed of the Phu Phan Formation is heavily weathered and dominated by coarse-grained pebbles. This weathering may have caused pebbles, granules, and coarse-grained sand to become trapped within cylindrical holes and potholes. On the other hand, the upper sandstone bed consists of homogeneous, well-sorted fine to medium sand grains, with a typical thickness of 2-3 meters. Mega cross-beddings with a pebble grain orientation along the foreset and bottomset are common. In areas where potholes are abundantly exposed, the sandstone strata have a dip angle of less than 5° and are sub-horizontal. There is also a sizable pool with numerous small potholes located in the middle of the bed.

Potholes have an aesthetically pleasing morphology and often attract tourists to world-renowned national parks. The Samphunbok area has a large number of potholes located within the Mekong River bankfull elevation (approximately 1 km in width) along the river's length of approximately 5.3 km from north to southeast. These potholes form in special geological conditions, particularly in the central part of a synclinal form where the bedding angle is nearly horizontal (Choowong et al., 2013). Potholes only appear at Samphunbok from November to May when the water level drops during winter and summer. The bankfull elevation of the Mekong River is approximately 125 meters above the present mean sea level (MSL). In the central part of the riverbed, two large canyons are being developed, and the canyon bed is slightly higher than the present Mekong River level. Therefore, potholes inside the canyon will only be reactivated in their formation during seasons of flooding (July - October).

Moreover, in the Ubon Ratchathani province, along the Mekong River, there are many erosional features, such as potholes, pedestal rock, and other prominent weathering products of the Earth's surface processes. These features will be discussed in the following topic.

4.1.1 Typology of Potholes

One of the most striking features of Samphunbok is the relief of approximately 20 meters between the highest sandstone bed in the Mekong bankfull level (September) and the normal water level during the winter and summer (November - April). Potholes are forming at different altitudes within the sandstone riverbed, but it is more common for them to form in the middle of a bankfull elevation than towards its edges. One possible explanation for this is the location of the highest bed, which rarely experiences water level. On the other hand, potholes on the uppermost sandstone bed continue to form as a result of mega floods that create an overbank flow regime. These potholes are predominantly oval-shaped single and compound potholes, while connect or coalesced potholes are abundant in the lower sandstone bed at a level similar to the usual Mekong River water level, as seen in Figures 4.1a and b. In Figures 4.2a and b, the potholes in the lower sandstone bed can be seen. Figures 4.2a and b show that the middle sandstone bed is dominated by large ponds with few potholes.

In the upper bed, there is a well-known mickey-mouse-shaped pothole, which is a compound pothole consisting of one large and two smaller potholes, as seen in Figure 4.3.

This topic categorizes the typology of potholes at Samphunbok using various criteria, including location, size, shape, secondary sculpture, pothole connection, and relationship with structure, such as joint and fracture. The new typology established by this study will be instrumental in further understanding the formation and development of potholes at Samphunbok. Figure 4.4 illustrates the typology of potholes, providing a visual representation of the different categories and subcategories.

In conclusion, Samphunbok is a unique location for studying pothole formation and development. The relief between the highest sandstone bed and the normal water level during winter and summer creates ideal conditions for pothole formation. The new typology established in this study using various criteria will help scientists and geologists to better understand the formation and development of potholes at Samphunbok.

Figure 4.1 The photograph depicts the occurrence of coalesced potholes, with (a) showcasing a coalesced pothole and (b) depicting an active coalesced pothole situated close to the typical Mekong river level (Udomsak et al., 2021).

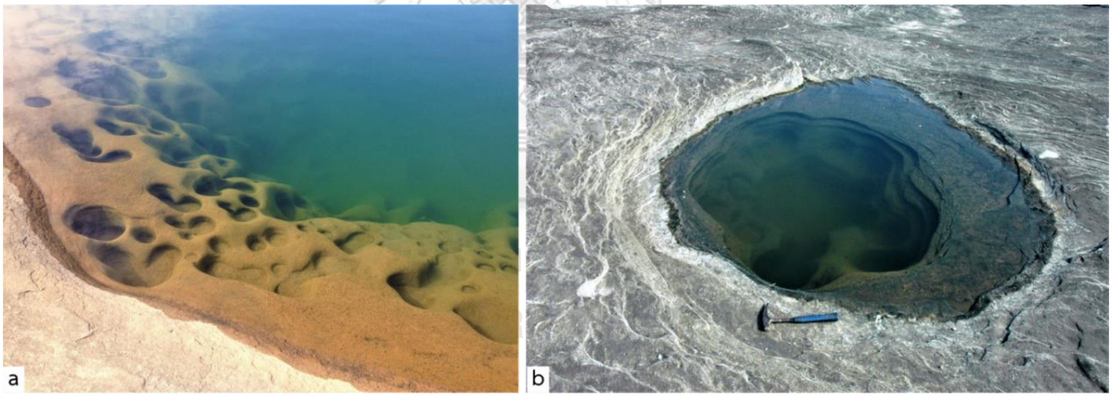


Figure 4.2 The photograph depicts a) a large pool with a smaller pothole inside it and b) a shallow round pothole with a small pothole inside on the top bed that is reactivated during the flooding season (Udomsak et al., 2021).

Figure 4.3 A large pothole and two smaller potholes connect together to form the famous Mickey Mouse shape at Samphunbok.

Typology of Potholes

Structural Control Pothole

- Ovoid Pothole
- Coalesced Pothole

Non Structural Control Pothole

- Ovoid Pothole
- Lateral Pothole
- Open Lateral Pothole
- Hierarchical Pothole
- Coalesced Pothole

Figure 4.4 A flow chart has been created to illustrate the typology of potholes at Samphunbok.

4.1.1.1 Structural Control Pothole

The potholes observed at Samphunbok can be divided into two categories: structural control potholes, which are related to fractures, and non-structural control potholes (Choowong et al., 2013). The shape of the potholes in the controlled group is determined by fractures of varying sizes, and they are named based on their mode of development. The potholes can form in both small- and large-scale fractures, and they are generally simple and oval-shaped, as depicted in Figure 4.5a. While oval potholes usually form within the large fracture, they are not very deep, as shown in Figure 4.5b. Half-oval-shaped potholes form along deeply fractured planes, as seen in Figure 4.6, and their future shape difficult to be predicted. Choowong et al. (2013) refer to these potholes as incompletely connected coalesced potholes because they are interconnected. They form along both large, straight fractures (Figure 4.7a) and large, non-linear fractures (Figure 4.7b). Coalesced potholes can also create furrows within the groove of a mega-cross bedding plane, as shown in Figure 4.8a. Additionally, coalesced potholes that are all connected and forming are present along large fractures, as seen in Figure 4.8b. Simple and compound types of structurally controlled potholes are found at Samphunbok. All of the potholes are developed in sandstone with varying textures.

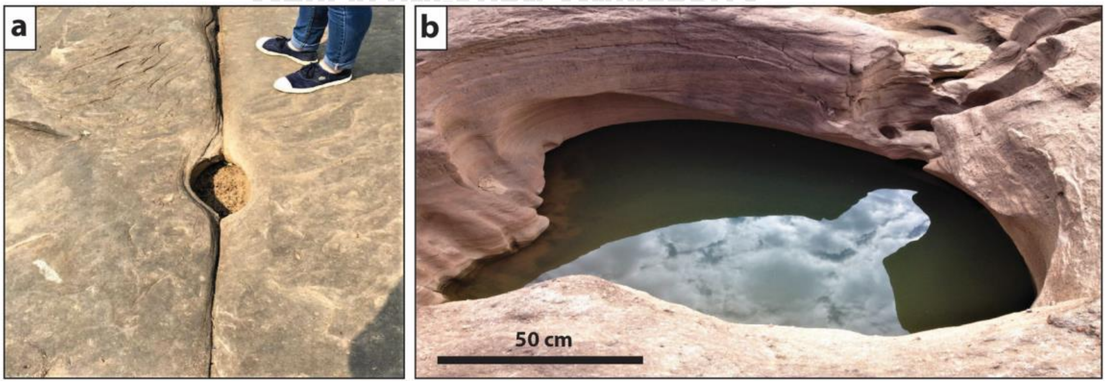


Figure 4.5 The photo depicts two types of potholes with structural control: a) a small oval-shaped pothole in the fracture, and b) a large shallow pothole in the fracture.

Figure 4.6 The photo showing a pothole with a half-oval shape formed along the fracture plane.

Figure 4.7 The photo displaying two examples of structure controlling potholes: a) The potholes forming along a straight fracture, and b) The potholes forming in a large but not straight fracture.

Figure 4.8 The photograph displays two types of coalesced potholes. The first type a) is formed within the furrow of a mega-cross bedding plane, while the second type b) is created along the fracture plane connect into coalesced pothole.

4.1.1.2 Non Structural Control Pothole

The second group of potholes at Samphunbok is formed without any structural control, and these potholes are categorized based on their characteristics. These categories were adapted from Richardson and Carling (2005). These potholes can be observed along the rim of the Mekong bankfull elevation, from the uppermost concordant sandstone plane bed to the middle part, where thousands of them are present. This category is composed of various types of potholes, including Ovoid Pothole, Lateral Pothole, Open Lateral Pothole, Hierarchical Pothole, and Coalesced Pothole, which will be further explained in the following paragraph.

1) Ovoid Pothole

The ovoid potholes are up to twice as long compared to how wide in the direction of the current flow. At Samphunbok, these ovoid-shaped potholes are commonly occurring as newly forming potholes. Nonetheless, the form may be circular or elliptical (Sato, Matsuura, and Miyazaki, 1987). The circular shape of an ovoid pothole may be the first stage of a pothole's formation, and the elliptical shape may be the more evolved form of the circular pothole (Figure 4.9a) (Álvarez Vázquez and De Uña-Álvarez, 2017). The oval pothole may be evolve and expand size into the large oval pothole in the homogeneous sandstone (Figure 4.9b).

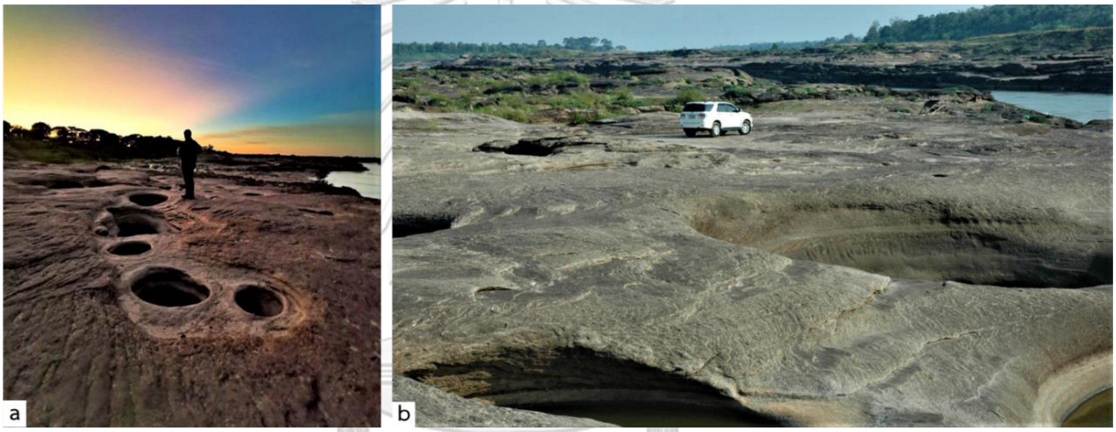


Figure 4.9 The photo of the oval potholes are a) single and simple pothole and they can evolve into a b) large oval pothole.

2) Lateral Pothole

The lateral pothole was described in research by Zen and Prestegaard (1994), which explain the incomplete near-vertical face pothole. The lateral pothole at Samphunbok was found on the large channel canyon wall. The surfaces of lateral potholes were concave and ranged in shape from nearly circular (when viewed horizontally, facing the sidewall) to elongate and vertically oriented furrows. The lateral pothole is normally found as a secondary erosion form inside a large pothole and on the sidewall of the channel rim (figure 4.10a and 4.11). Many of these lateral potholes at Samphunbok resemble those previously research by Richardson and Carling (2005) in Nam Mae Chaem (Ob Luang), Thailand.

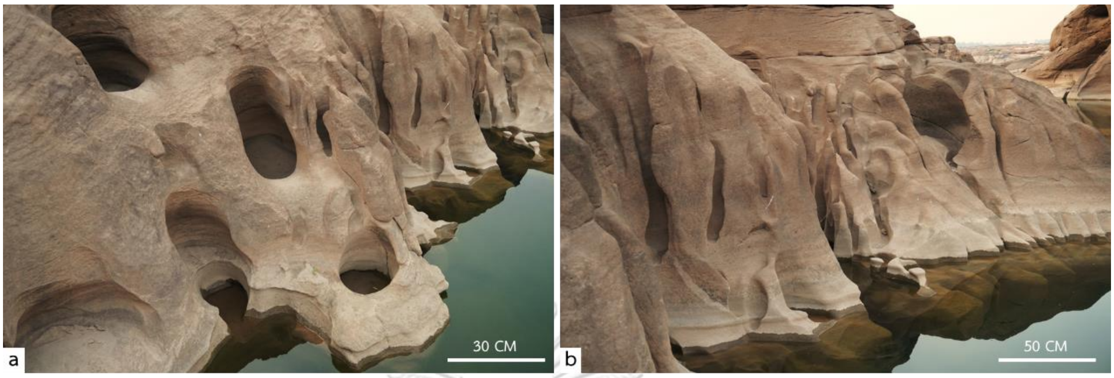


Figure 4.10 The photo show pothole occurs on the sidewall of channel a) lateral pothole b) Open lateral pothole.

3) Open Lateral Pothole

The open lateral pothole resembles the lateral pothole, but the floor of the open lateral pothole has been eroded to the point that it no longer contains the close depression, and the floor slopes towards the open side (figure 4.10b and 4.11). Zen and Prestegaard (1994) named the type as a “bucket-seat lateral potholes”. Because they are at least twice as high as they are wide, the lateral potholes are referred to as linear because of their shapes. These also have sharp rims on both sides, similar to those that were seen in the granitic gneiss of Nam Mae Chaem (Ob Luang), Thailand.

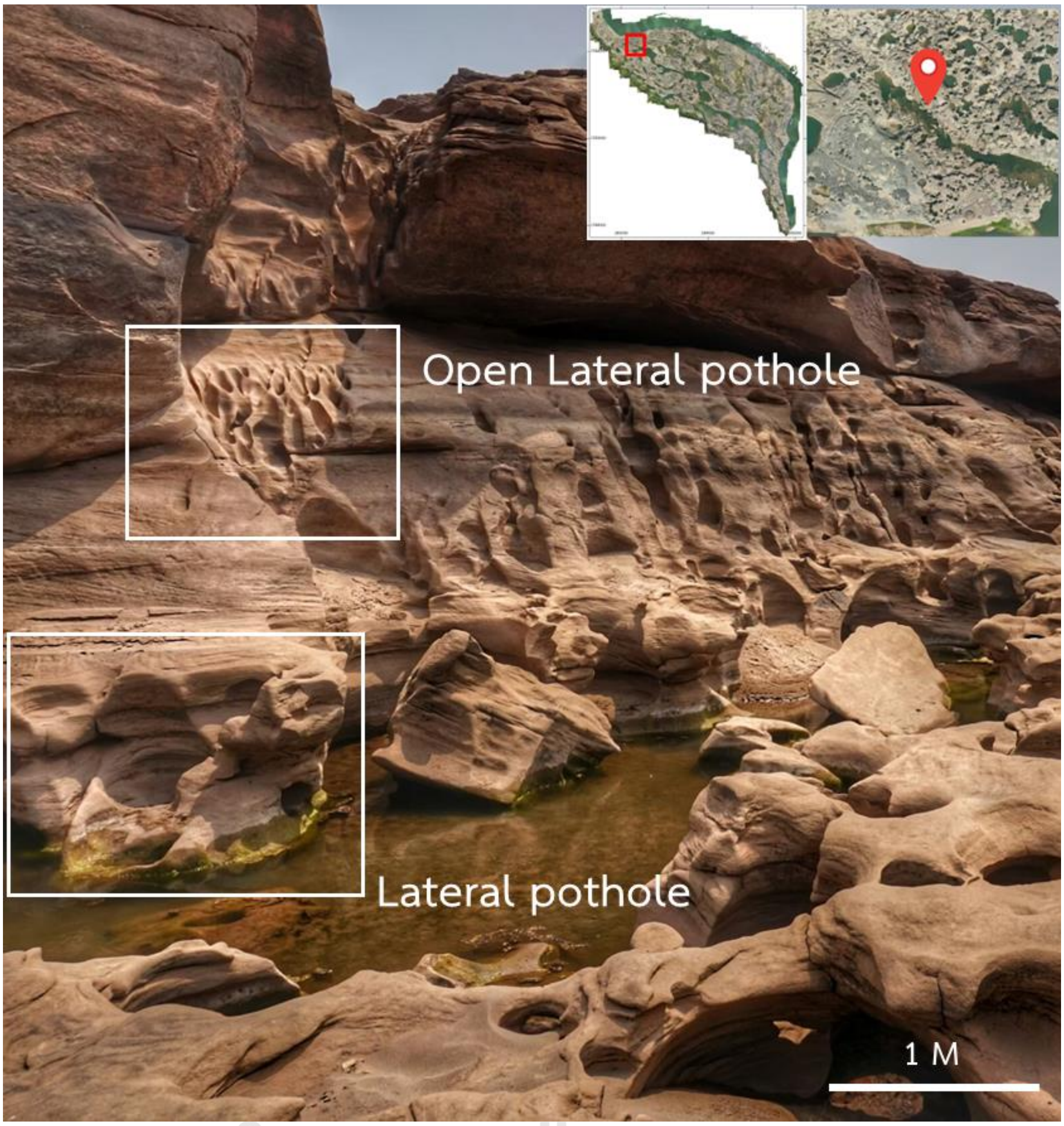


Figure 4.11 The lateral pothole and open lateral pothole on the sidewall of paleochannel in the canyon.

4) Hierarchical Pothole

The meaning of hierarchical pothole that from hierarchy means graded or rank. The hierarchical pothole are the large pool (Choowong et al., 2013) with the a lot of smaller or secondary pothole inside it, either in the floor or carved into and perched on the sidewalls (Figure 4.12a) (Richardson and Carling, 2005). In the Samphunbok area have many hierarchical pothole in the middle part of the canyon.

Locally known as "SraMorakot," the largest hierarchical pothole at Samphunbok is 30 meters long and 15 meters wide and is one of the most famous and well-known potholes in the Samphunbok region (Figure 4.2a). A second large hierarchical pothole is oval-shaped and shallow, measuring approximately 12 meters long and 8 meters wide. This large pool and the tiny potholes within are observable after they dry up (Figure 4.12b).

Figure 4.12 The photo shows that a) hierarchical potholes can occur in various sizes that have b) smaller potholes inside that appear in the summer when the water inside dries out.

5) Coalesced Pothole

Coalesced potholes are normally large and complex, with secondary carving inside (Figure 4.13a) (Nemec et al., 1982). Coalesced potholes can form at the bankfull level within a channel margin. A group of potholes in the process of coalescing can become interconnected while leaving large parts of their walls and rims intact, producing an outcrop with a "Swiss cheese" appearance (Figure 4.13b) (Richardson and Carling, 2005).

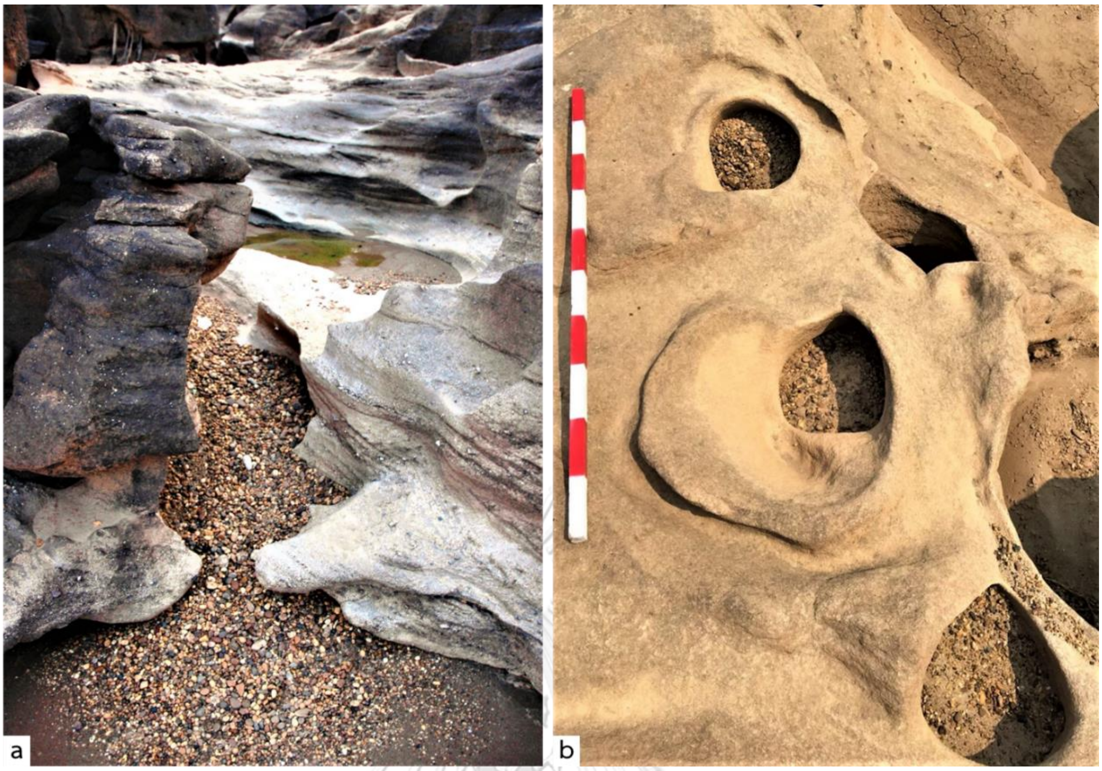


Figure 4.13 The photo shows: a) a coalesced pothole with a grinder inside b) the lateral pothole where the side wall was eroded and connected to the coalesced pothole.

4.1.2 Giant Pedestal

The giant pedestal (mushroom) rock (Figure 4.14) was surveyed in detail for its sedimentology and regional geological structures to clarify the process of being sculptured. As previously indicated, sandstone beds of the Phu Phan Formation, composed of pebbly sandstone and partially basal conglomerate (Choowong et al., 2013), developed the more resistant bed than the lower beds. The cap rock is normally 1–2 m thick. The lower sandstone beds are consisted of coarse-grained sandstone with granules. In the stratigraphic column of giant pedestal rock, it compose of 18 bed rock with different of lithology of Phu Phan Formation sandstone. The giant pedestal is approximately 10 m tall, and the internal sedimentary structures include cross-stratification, crossbedding, and very prominent normal grading (Figure 4.15a-d).

Figure 4.14 The giant pedestal rock is the largest pedestal rock in Thailand that has a fracture that divides the pedestal rock like twin rocks with the cap rock 1-2 meters thick.

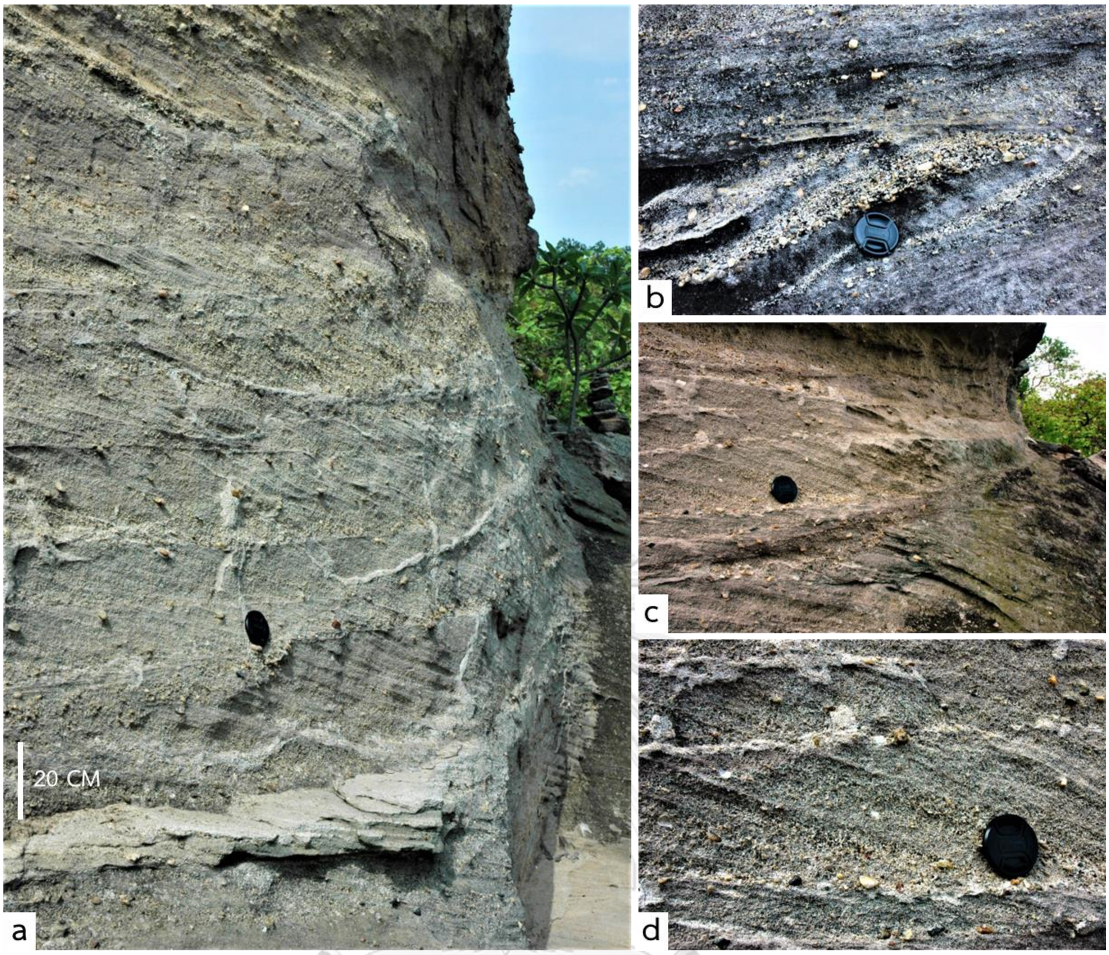


Figure 4.15 The sandstone of pedestal rock compose of sedimentary structure such as a) planar cross bedding on a clear surface b) the set of trough cross bedding c) and d) the close up photo show normal grading of gravel in the forest.

4.1.3 Tafoni

In the Samphunbok area at the Phachan cliff, where there are many weathered holes locally named "Sam Muan Roo" look like tafoni feature. Tafoni is a cavernous landform formed by the weathering of acid to intermediate plutonic rocks, including sandstone, limestone, and schist, and is found in semiarid climates (Fairbridge, 1968; Jennings, 1968). It is normally related to the mechanical disintegration of the rock caused by its saturation with salts and the crystallisation of these salts during repeated wetting and drying cycles (Sparks, 1972). Although the origin of tafoni in granite is well-described (De Uña-Álvarez, 2008; Twidale and Romaní, 2005), it continues to be controversial. Instead of being the result of salt crystallization, the tafoni at Samphunbok may have formed as a secondary deposit. They are predominant in the Phachun sandstone cliff as firstly horizontal holes eroded at Mekong water level (Figure 4.16a) and then holes formed by secondary deposition of silcrete in the crossbedding and cross-lamination (Figure 4.16b).

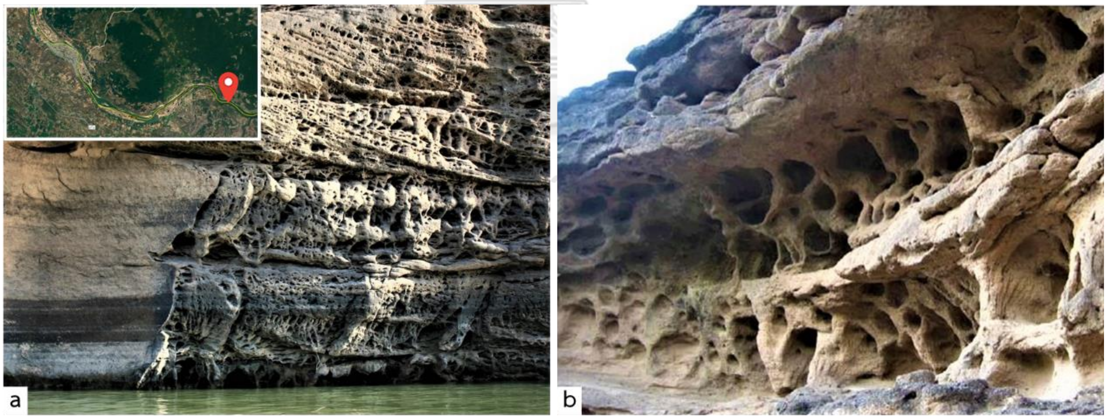


Figure 4.16 The photo showing tafoni at Phachan cliff a) near the level of Mekong river and b) form in secondary deposit in cross bedding.

4.1.4 Other Prominent Erosional Feature

Apart from the massive amounts of potholes at Samphunbok, several other dominant erosional features were found in the lower sandstone bed. Little pedestal mounds with a pebbly sandstone, conglomerate, and goethite coating were found as the remnants of erosional surface features (Fig. 4.17a). Similar "colour stone" features were recorded in Phachun cliff (Choowong et al., 2013). In the trough crossbedding, a highly weathered surface generates the amazing brain-like feature (Fig. 4.17b). This brain-shaped rock may have first evolved as a result of thermal expansion that caused surface cracks in the crossbedding. Then, water corrosion expanded the cracks. The other interesting feature is a natural arch (Figure 4.18), where the side wall has eroded away. Natural arches are discovered in breached and coalesced potholes in which the breaching of the wall occurred below the pothole's rim and never continued to remove every side of the pothole wall. As a result, a little part of the wall on the side that was breached is still standing, allowing water to flow out of the pothole. They are referred as either arches or pillars, relying on the orientation of the remnant limb (Blank, 1958; Jennings, 1983; Kale and Shingade, 1987; Nemec et al., 1982).

Figure 4.17 The other erosional remnant in the Samphunbok area a) the color stone has a goethite coating on the surface b) the brain-like rock is the result of thermal expansion.

Figure 4.18 The photo showing the natural arch and potholes in the Samphanbok study area.

4.2 Stratigraphic Column of Samphanbok Area

In the Samphanbok area, three stratigraphic columns were constructed (Figure 4.19). The first column, called the Ban Song Khon column, is situated to the north of the Samphanbok area. This column reveals the contact between the Sao Khua Formation and the Phu Phan Formation. In this column, the Sao Khua Formation consists of reddish-brown sandstone with a very fine to fine sand grain size. Each bed in the formation contains calcrete near its surface. The Phu Phan Formation in this column is composed of brownish-grey sandstone with a grain size ranging from very coarse sand to pebbles, interspersed with fine to medium sand layers.

The second column, known as the Samphanbok column, is located within the Samphanbok canyon. This column is made up of Phu Phan Formation sandstone, characterized by medium to pebbly sandstone with trough and planar crossbedding.

The final column is the giant pedestal rock column, found near Phachan, approximately 1 kilometer away from the Mekong River. The lithology of this column also consists of Phu Phan Formation sandstone, specifically medium to pebbly sandstone with trough and planar crossbedding. It is likely that this column represents the topmost bed of the Phu Phan Formation in the area.

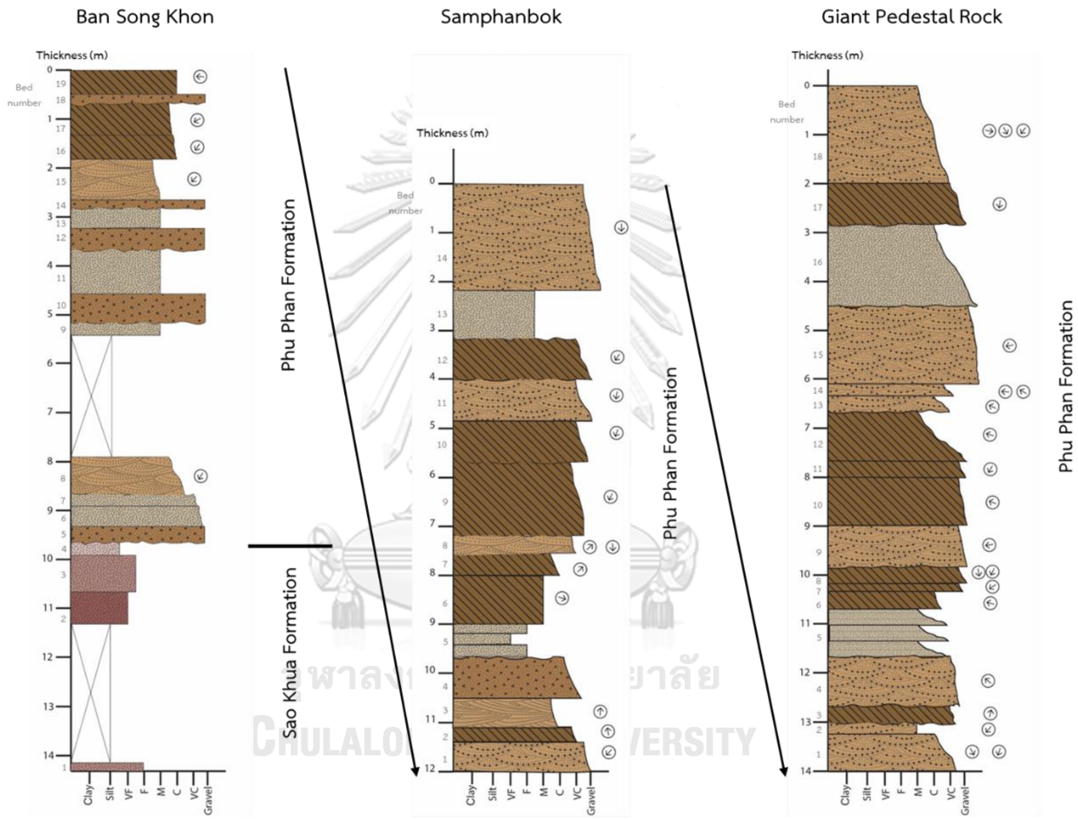


Figure 4.19 The illustrate showing the stratigraphic column of study area, compose of Ban Song Khon Column at the bottom, Samphanbok column in the middle and giant pedestal rock column at the top.

4.3 Analyze Pebble Counting Related to the Occurrence of Pothole

The pothole forming by water flow into the joint or fracture and generate vortex inside the fracture. Normally, in the river when water flow it transfer sediment together. The sediment falls into the hole and starts rotating inside it, becoming a grinder inside the pothole. The sandstone of Samphanbok consists of pebbly sandstone. The flow velocity of the Mekong river is may not strong enough to bring the pebble, which is bedload, to the uppermost bed. The grinder inside a pothole falls from the pebbly sandstone bed by the weathering process, not by transport from upstream. So, the erosion rate of the pothole is related to the pebble volume inside the sandstone bed where the pothole is located. Moreover, the pothole of the lower sandstone at Samphanbok has a higher erosional rate than the upper sandstone bed because the pebbles that fall from the upper bed to the lower bed increase the volume of grinder in the pothole in the lower bed.

The pebble in the pebbly sandstone bed was calculated the density of pebble by used the comparison chart for estimate composition of sandstone (Lindholm, 1987). Concerning the chart, there exists a pebble within the sandstone bed that is regarded as a clast, while the sand is deemed the matrix. In the vicinity of bed 14 on the uppermost layer of Samphanbok, the proportion of pebbles inside the sandstone bed is estimated to be approximately 10%. This pebble, which is situated in bed 14, exhibits sub-rounded characteristics, medium sphericity, and is composed of 80% quartz and 20% quartzite (Figure 4.20).

Next, the pebble inside the bed 11 in the sandstone bed have proportion of pebbles is estimated to be approximately 7%. This pebble, which is situated in bed 11, exhibits sub-rounded characteristics, medium sphericity, and is composed of 60% quartz, 30% quartzite and rock fragment 10% (Figure 4.21).

Following that, bed 9 of the sandstone bed contains a pebble that is estimated to constitute around 5% of the bed's total composition. This pebble, located in bed 5, exhibits distinctive characteristics such as sub-rounded shape and medium sphericity. It is primarily composed of 90% quartz and 10% quartzite (Figure 4.22).

Lastly, bed 4 is the closest bed to the level of the Mekong river and comprises approximately 30% of pebble composition. The pebbles present in bed 4 exhibit sub-rounded characteristics and medium sphericity, and are composed of 80% quartz, 10% quartzite, and 10% rock fragment (Figure 4.23).

The sub-rounded shape of the pebble suggests that it has undergone significant transportation before being deposited in the sandstone bed. Additionally, the medium sphericity of the pebble indicates that it has not been subjected to extensive abrasion during transportation, which is consistent with the sub-rounded shape.

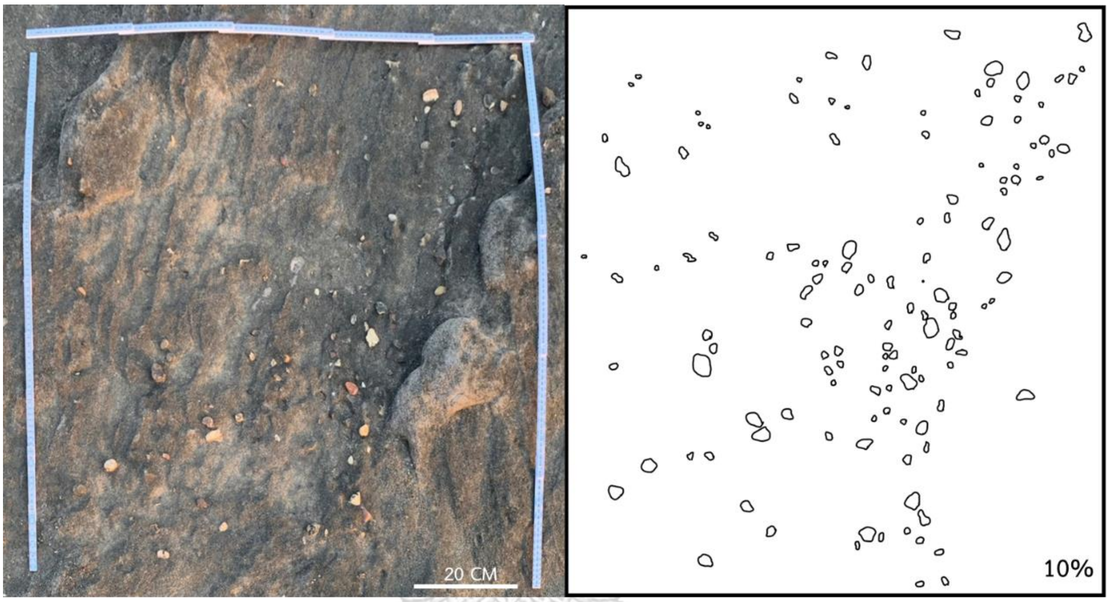


Figure 4.20 Pebble composition of top bed 14 of Samphanbok.

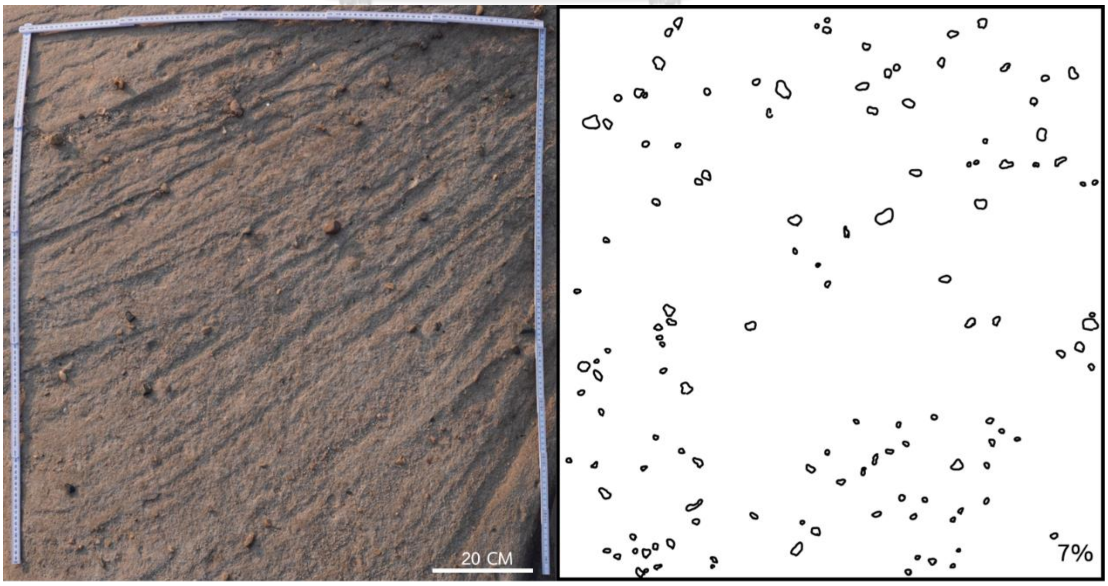


Figure 4.21 Pebble composition of bed 11 of Samphanbok.

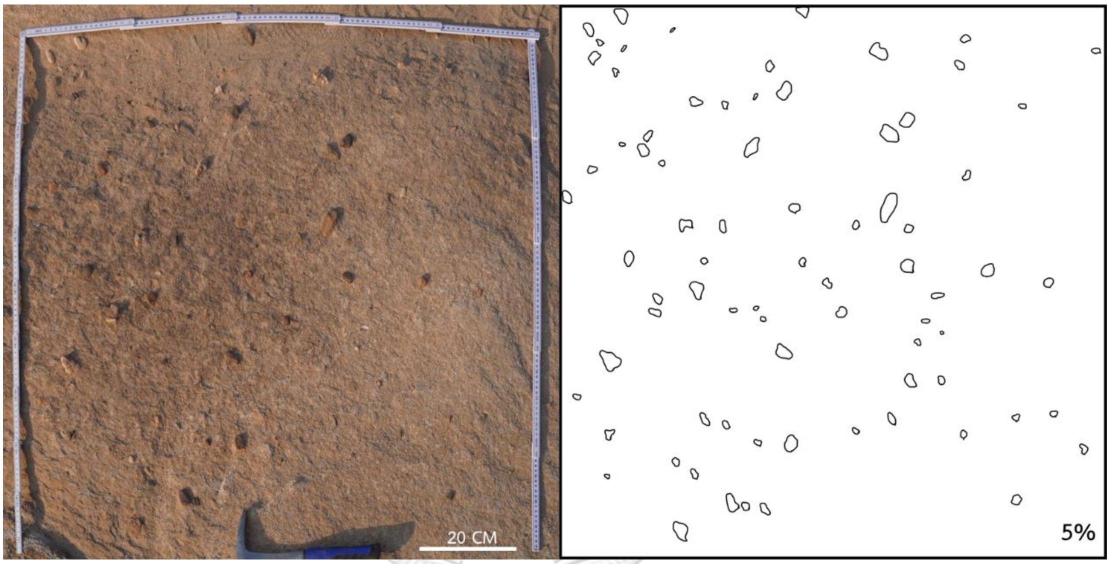


Figure 4.22 Pebble composition of bed 9 of Samphanbok.

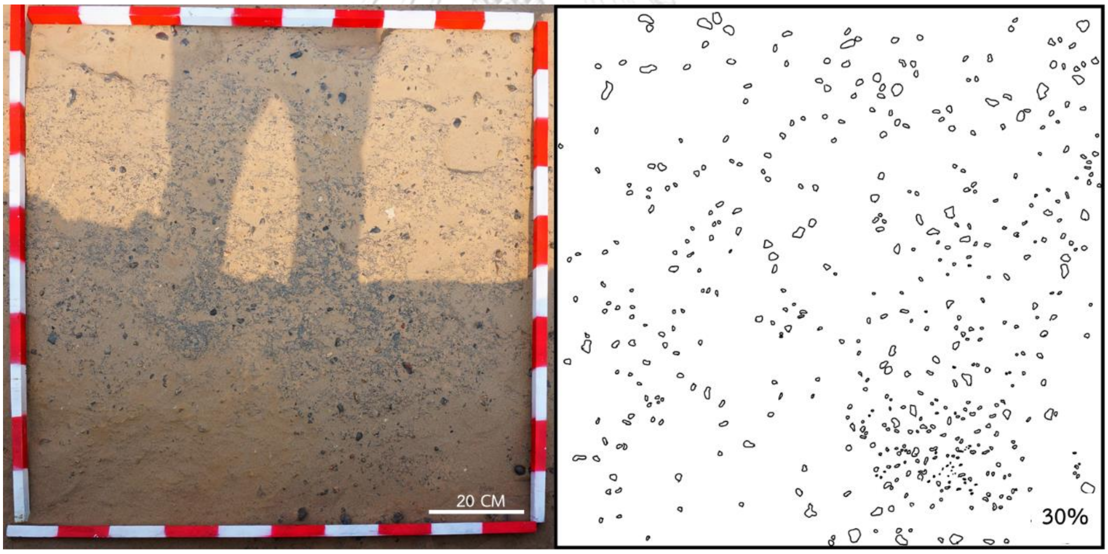


Figure 4.23 Pebble composition of bed 4 of Samphanbok.

The grinder found in the pothole is associated with the pebble inside the sandstone bed. This pebble originated from the representative bed where the pothole was formed. To analyze the pebble, it was collected and sieved to separate the size of the grinder from pebble to silt. The grinder from bed 12, which is situated near the top, was composed of 76.64% pebble, 18.63% granule, 3.64% very coarse sand, 0.63% coarse sand, 0.14% medium sand, 0.25% fine sand, 0.13% very fine sand, and 0.12% silt (Figure 4.24).

The next sample from pothole located between bed 8 to bed 9 was composed of 0.14% coarse sand, 6.32% medium sand, 84.38% fine sand, 8.9% very fine sand, and 0.26% silt (Figure 4.25).

Finally, the grinder sample taken from bed 4 which the nearest pothole from water level at Mekong River was composed of 20.38% pebble, 19.19% granule, 14.44% very coarse sand, 12.32% coarse sand, 12.46% medium sand, 15.16% fine sand, 3.91% very fine sand, and 2.15% silt (Figure 4.26).

The percentage composition of the grinder's size in the potholes situated in bed 4, bed 8-9, and bed 12 revealed a correlation between the volume of pebbles in the sandstone bed and the grinder in the pothole. When the density of pebbles in the sandstone bed is high, the volume of pebbles and granules in the grinder within the pothole is also high. Additionally, potholes located in lower sandstone beds have the potential to accumulate pebbles that fall from upper beds, thereby increasing the volume of pebbles in the potholes at the lower level.

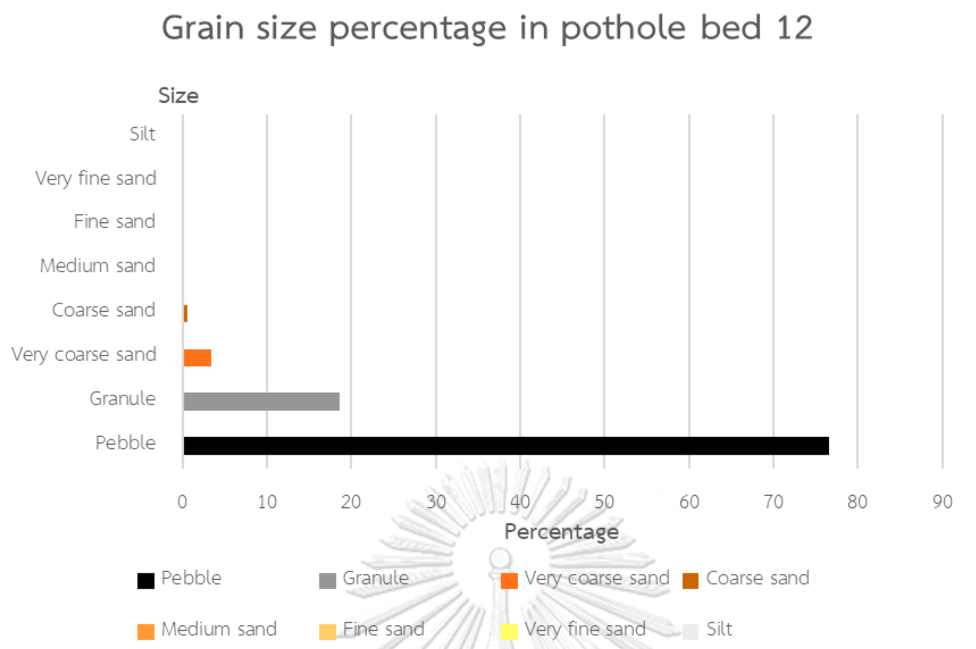


Figure 4.24 The diagram illustrates the size composition of the grinder found in the pothole located in bed 12 of Samphanbok.

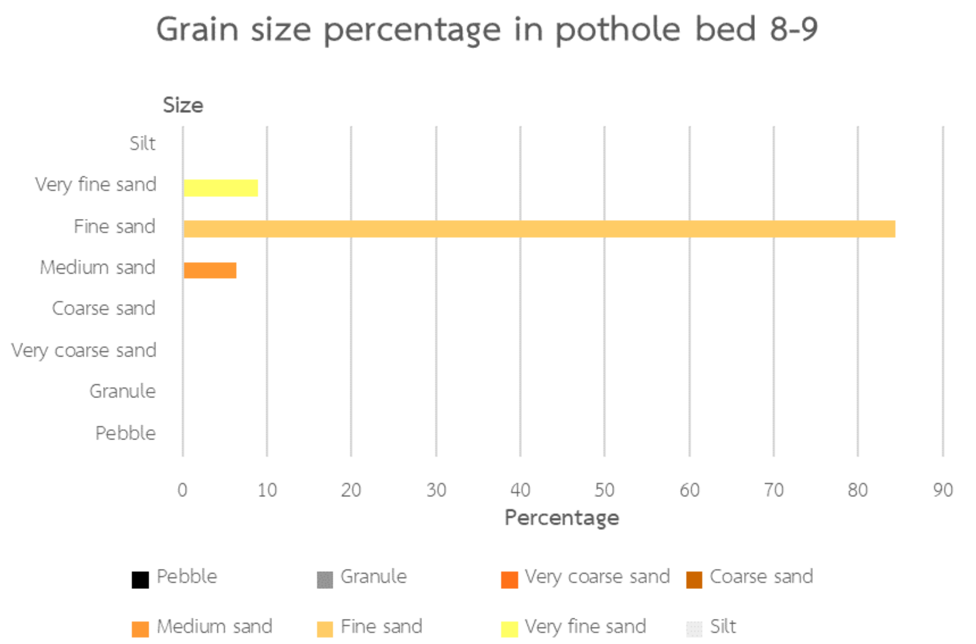


Figure 4.25 The diagram illustrates the size composition of the grinder found in the pothole located in bed 8-9 of Samphanbok.

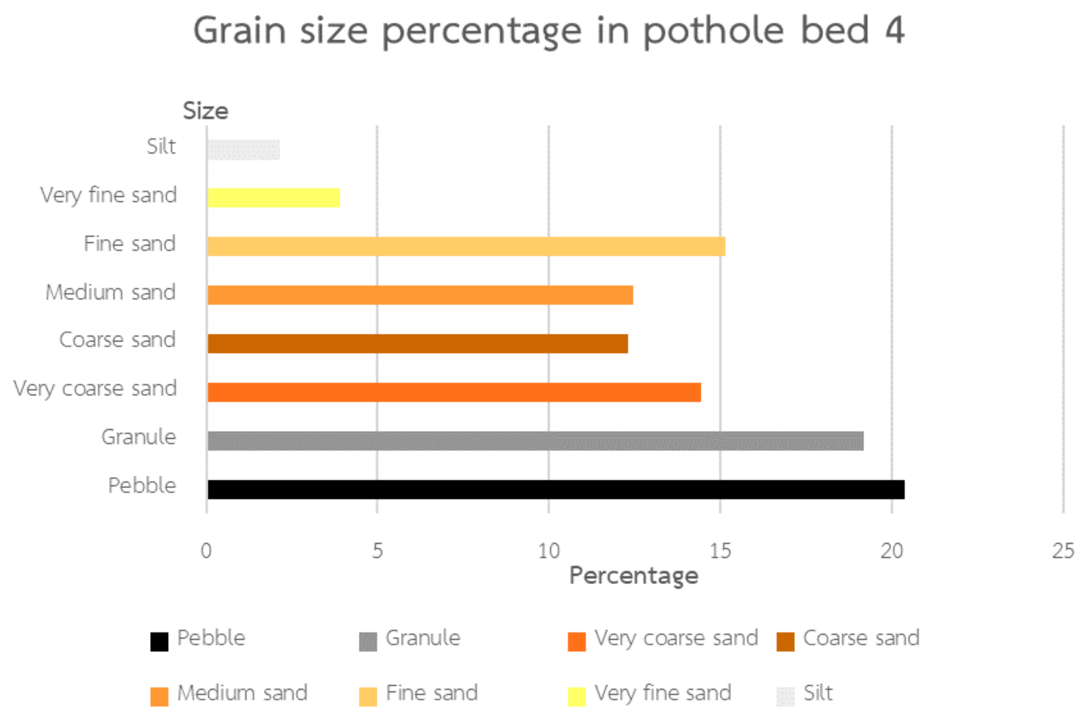


Figure 4.26 The diagram illustrates the size composition of the grinder found in the pothole located in bed 4 of Samphanbok.

There are potholes containing grinders that are larger than pebble size or 64 millimeters. These grinders are roughly the size of cobbles to boulders and originate from bedrock that has cracked and collapsed onto lower bedrock. Over time, the loose blocks have been eroded by sediment in running water and have become smoother and smaller. The lithology of these boulders is similar to the surrounding bedrock, but they do not function as grinders because the vortex current is not strong enough to move them around inside the pothole until they become small enough to be moved (Figure 4.27).

Figure 4.27 The photo shows the boulder inside the pothole a) the loose block fall on the sandstone bed b) the boulder was erode and become smaller c) the sub-round boulder inside the pothole.

4.4 Density of Pothole

The density of pothole determines by using the DJI Mini 3 Pro capture the ariel photo. Base on analysis of photograph the density of pothole can be classified into three groups: firstly, a high density of potholes, which indicates the presence of more than 10 potholes in an area of 100 square meters; secondly, a moderate density of potholes, which is characterized by the presence of around 5-10 potholes in an area of 100 square meters; and lastly, a low density of potholes, which refers to the presence of less than 5 potholes in an area of 100 square meters (Figure 4.28).

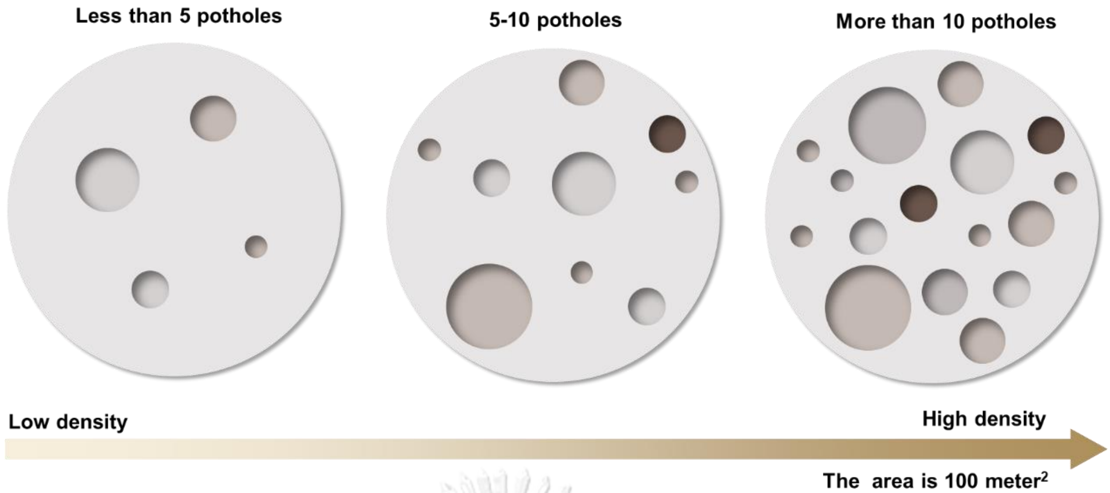


Figure 4.28 The illustrate show the classification of density of pothole at Samphanbok.

By utilizing drone-captured aerial photographs, a detailed map of the Samphanbok Geological Heritage Site was created with higher resolution compared to the available satellite images on Google Earth. This allowed for a more accurate observation of the density and location of potholes. It was discovered that the high-density pothole zone is concentrated at the rim of the Mekong River, where the water current is particularly strong. This zone also includes the cutbank zone, which is a popular tourism destination. This zone area is around 5% of Samphanbok area. Adjacent to the high-density zone is the moderate density pothole zone, where the water current is comparatively weaker. Moreover, the moderate density potholes can be observed at the rim of the paleo channel, which became active during periods of drowning. The area of this zone is around 4% of Samphanbok area. The low-density pothole zone is primarily located in the inner canyon zone near the bank of the Mekong River, where the water current is relatively weak. This zone is also situated on the topmost bed, which became active during mega flood events (Figure 4.29). the area of low-density pothole zone around 62%. Moreover, in Samphanbok area have many unidentified zones, they cover with sediment and vegetable on the surface. This area of unidentified zones approximately 18% (Figure 4.30).

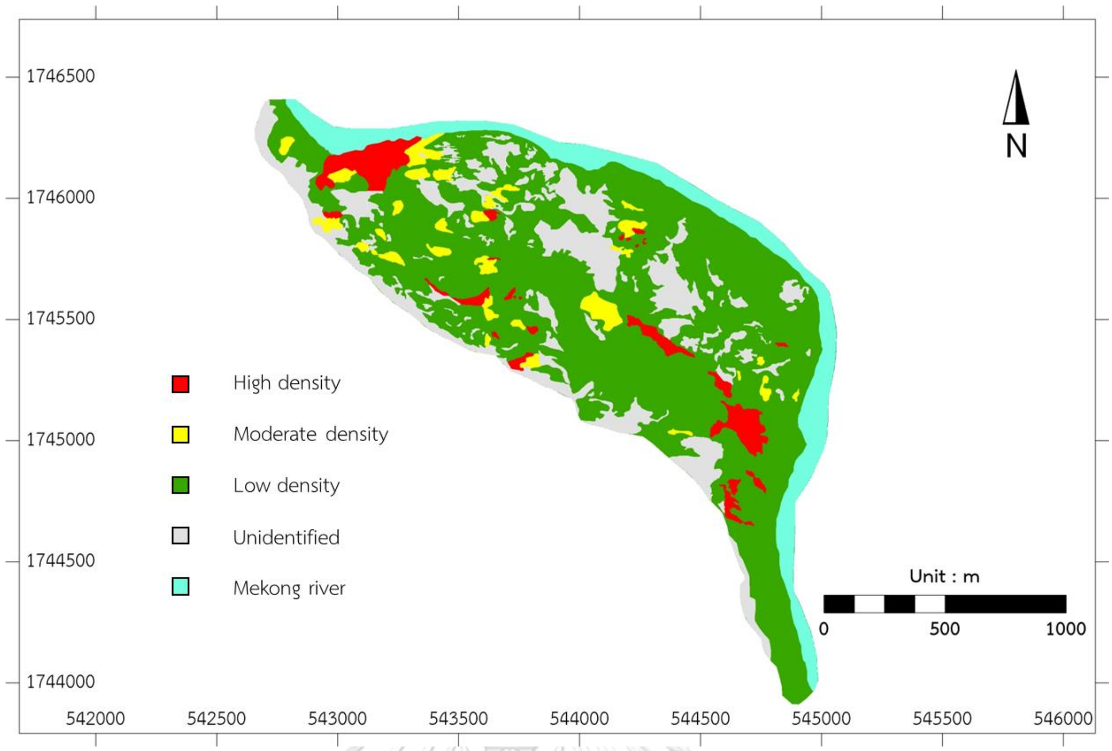


Figure 4.29 The map view of Samphanbok area show the density of pothole in the canyon.

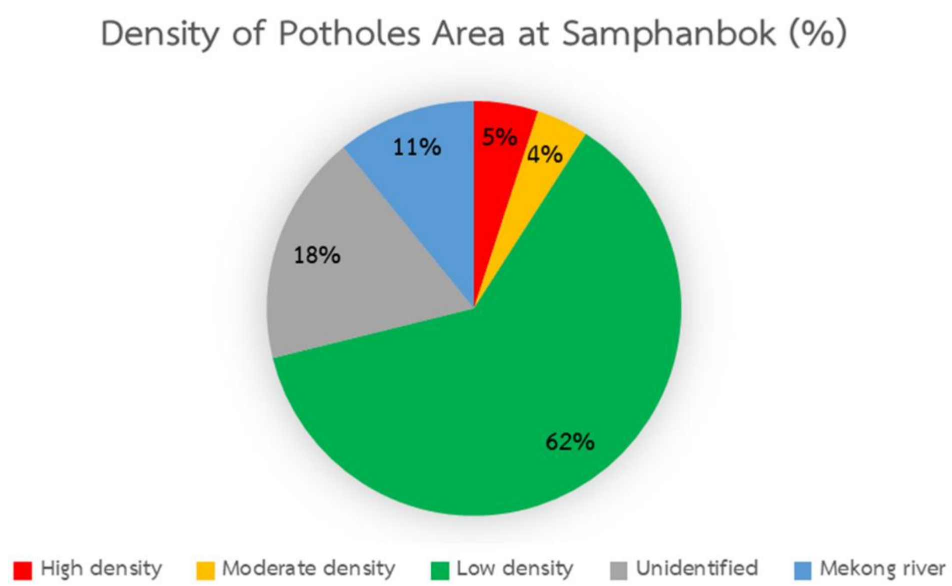


Figure 4.30 The diagram showing the percentage of density zone area including unidentified zone and Mekong River.

4.5 Stratigraphy, Lithofacies and Architectural Element

The lithofacies in the Samphanbok area are studied from the lithology and sedimentary structure in the stratigraphic column. Samphanbok has three interesting outcrops for building the stratigraphic column. The first is located in the north of Samphanbok near Ban Song Khon, which is the contact between the Sao Khua Formation and the Phu Phan Formation (Figure 4.31). The second is located in the canyon of Samphanbok (Figure 4.32), and it is the Phu Phan Formation Sandstone. The last one is the giant pedestal rock near the Phachan area (Figure 4.33).

4.5.1 Lithofacies of Ban Song Khon canyon

The lithofacies from Ban Song Khon stratigraphy was classified by using the method from Miall (1977b, 1985) can be divide into six lithofacies. Such as one gravel facies compose of bedded gravel (Gm). Three of the sandy facies recognized by trough crossbedding (St), planar cross bedding (Sp) and horizontal lamination (Sh). Finally, two facies of the fine-grained clastic facies are fine sand to mud with lamination and ripple mark (Fl) and the massive bed of site and mud (Fm).

There are three facies associations for six lithofacies: gravel lithofacies, sand lithofacies, and fine-grained clastic facies. The specifics are provided below.

Association 1: gravel lithofacies

1) Facie Gm: Bedded gravel

This facie is composed of a massive bed of gravelly sandstone. The grain size of this facie ranges from very coarse sand to pebbles with poorly sorted materials. The pebble is round to sub-round, and the thickness of this facie is approximately 0.3–0.7 meters. The bottom of this facies may find the erosional surface This facie indicates the longitudinal gravel bar in the channel.

Association 2: sand lithofacies

2) Facie St: Trough cross-bedding

This facie is composed of medium to very coarse sandstone. The major structure is trough cross-bedding. The thickness of this facie is around 0.7-0.8 meters. This facies indicates the channel bed.

3) Facie Sp: Planar cross-bedding

This facie consists of medium to coarse sandstone. The major structure is planar cross- bedding. The thickness of this facie is around 0.5-0.7 meters. This facies indicates the transverse and linguoid bar.

4) Facie Sh: Horizontal lamination

This facie compose of medium sandstone and some bed is medium to pebbly sandstone. In this facie did not find the noticeable structure. The thickness of this facie approximately 0.2-0.9 meters. This facies indicates the planar bed flow.

Association 3: Fine grained lithofacies

5) Facie Fl: Fine lamination

This facie is composed of fine sandstone. This facies lacks the noticeable sedimentary structure, it has only the lamination. The thickness of this facie around 0.1-0.2 meters. This facies indicates the overbank or flood deposit.

6) Facie Fm: Massive silt, calcrete

This facie is composed of silt to fine sandstone. This facie found the carbonate nodule or calcrete. The thickness of this facie around 0.2-0.7 meters. The calcrete indicates semi-arid climate and also indicate the paleosols.

Table 4.1 The summary of lithofacies and interpretation of the Ban Song Khon canyon modified from Miall (1977a).

Facies code	Lithofacies	Sedimentary structure	Interpretation
	Gravel lithofacies		
Gm	Crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bar
	Sand lithofacies		
St	Sand, medium to v. coarse, may be pebble	Trough crossbedding	Dune, channel bed
Sp	Sand, medium to v. coarse, may be pebble	Planar crossbedding	Transverse and linguoid bar
Sh	Sand, fine to v. coarse, may be pebble	Horizontal lamination	Planar bed flow
	Fine grained lithofacies		
Fl	Sand, silt, mud	Fine lamination, small ripple mark	Overbank or flood deposit
Fm	Silt, mud	Massive, calcrete	Overbank, paleochannel

4.5.2 Architectural element of Ban Song Khon canyon

Based on Miall (1977b, 1985) these elements characterized by their geometries and bounded surfaces are used as a basis for interpreting the depositional environment. Four architectural elements were recognized: channel (CH), sandy bedform (SB), gravel bar and bedform (GB) and overbank fines (OF).

Architectural formed in channel.

1) Element CH: Channel

In this area channel element (CH) compose of lithofacies Gb at the lower part and overlaying with lithofacies St and Sp. This element found on the upper most of Ban Song Khon canyon which is the Phu Phan Formation sandstone. This element indicates as a channel that have the gravel on the riverbed and top up with the channel fill and minor bar.

2) Element SB: Sandy bedform

In this area, sandy bedform (SB) is normally found with gravel bar bedform (GB) as a result of lateral facies change. Sandy bedform at Ban Song Khon consists of planar cross-bedding in lithofacies Sp and lamination in lithofacies Sh. This element indicates a sandy bedform, which is a channel fill or may occur as a minor bar.

3) Element GB: Gravel bar bedform

In this area, gravel bar bedform (GB) is normally found with sandy bedform (SB) as a result of lateral facies change. Gravel bar bedform at Ban Song Khon consist of thin bed of gravel in lithofacies Gm interbedded with laminated sand in lithofacies Sh. This element indicates a gravel bar in the middle of channel.

Architectural formed on the overbank environment.

4) Element OF: Overbank fines

In this study area overbank fine (OF) compose of fine lamination of silt to fine stone of lithofacies Fl and massive very fine sandstone of lithofacies Fm. This element shows the origin of vertical aggradation that indicate overbank flow near the active channels and the depositional environment of flood plain because in the Fm facies found the calcrete that indicates the paleosols. However, this element usually erodes by the cutbank of channel.

Table 4.2 The summary of architectural element and interpretation of the Ban Song Khon canyon modified from Miall (1985).

Element	**Symbol**	**Principal lithofacies assemblage**	**Geometry and relationship**
Channel	CH	Any combination	Concave up erosional base, internal concave up secondary erosional surface
Sandy bedform	SB	Sp, Sh	Channel fill, lens, sheet, minor bar
Gravel bar and bed form	GB	Gm	Lens, blanket
Overbank fines	OF	Fl, Fm	Thin to thick blanket, interbedded with SB

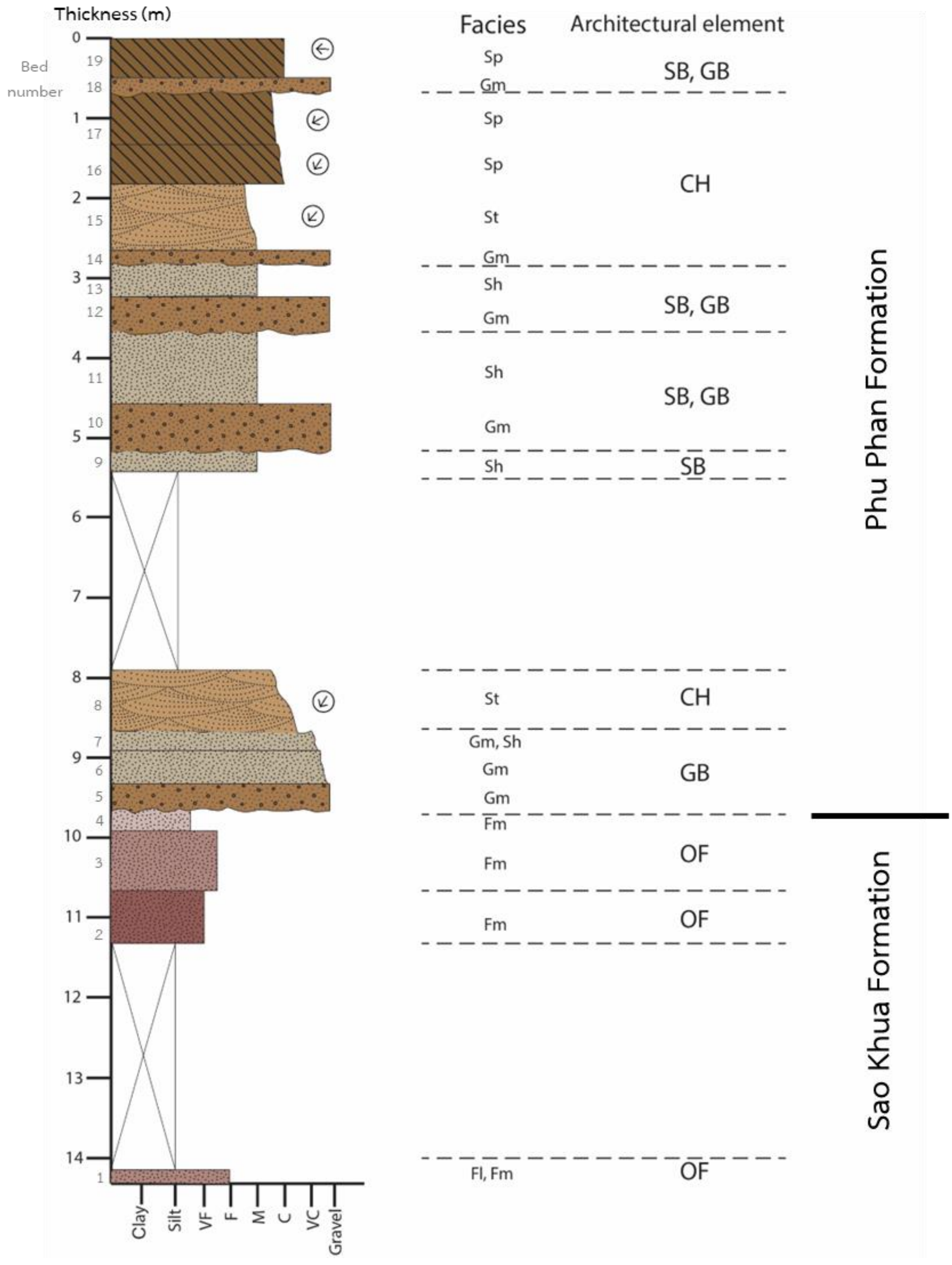


Figure 4.31 The stratigraphy with Paleo current of contact between Sao Khua Formation and Phu Phan Formation at Ban Song Khon canyon.

4.5.3 Lithofacies of Samphanbok canyon

The lithofacies from Samphanbok canyon stratigraphy was classified by using the method from Miall (1977b, 1985) can be divide into four lithofacies. Such as one gravel facies compose of bedded gravel (Gm). Three of the sandy facies recognized by trough crossbedding (St), planar cross bedding (Sp) and horizontal lamination (Sh).

There are two facies associations for four lithofacies: gravel lithofacies and sand lithofacies. The specifics are provided below.

Association 1: gravel lithofacies

1) Facie Gm: Bedded gravel

This facie composed of a massive bed of gravelly sandstone. The grain size of this facie ranges from coarse sand to pebbles with poorly sorted materials. The pebble is round to sub-round, and the thickness of this facie is approximately 0.8-0.9 meters. The bottom of this facies may find the erosional surface This facie indicates the longitudinal gravel bar in the channel.

Association 2: sand lithofacies

2) Facie St: Trough cross-bedding

This facie composed of the medium to pebbly sandstone. The major structure is trough cross-bedding. The thickness of this facie around 0.4-2.2 meters. This facies indicates the channel bed.

3) Facie Sp: Planar cross-bedding

This facie consists of medium to very coarse sandstone. The major structure is planar cross- bedding. The thickness of this facie around 0.3-1.5 meters. This facies indicates the transverse and linguoid bar.

4) Facie Sh: Horizontal lamination

This facie composes of very fine to fine sandstone. In this facie did not find the noticeable structure. The thickness of this facie approximately 0.2-1 meters. This facies indicates the planar bed flow.

Table 4.3 The summary of lithofacies and interpretation of the Samphanbok canyon modified from Miall (1977a).

Facies code	Lithofacies	Sedimentary structure	Interpretation
	Gravel lithofacies		
Gm	Crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bar
	Sand lithofacies		
St	Sand, medium to v. coarse, may be pebble	Trough crossbedding	Dune, channel bed
Sp	Sand, medium to v. coarse, may be pebble	Planar crossbedding	Transverse and linguoid bar
Sh	Sand, fine to v. coarse, may be pebble	Horizontal lamination	Planar bed flow

4.5.4 Architectural element of Samphanbok canyon

Based on Miall (1977b, 1985) these elements characterized by their geometries and bounded surfaces are used as a basis for interpreting the depositional environment. Four architectural elements were recognized: channel (CH), sandy bedform (SB), gravel bar and bedform (GB) and laminated sand sheet (LS). The detail of these architectural element are described below.

Architectural formed in channel.

1) Element CH: Channel

In this area channel element (CH) compose of trough cross-bedding in lithofacies St, planar cross-bedding in lithofacies Sp, and lamination of lithofacies Sh. This element found associate with element SB because of channel migration. This element indicates as a channel that have a changing from riverbed to channel bar and flood plain

2) Element SB: Sandy bedform

In this area, sandy bedform (SB) form in the sand dominated river compose of trough cross-bedding in lithofacies St and planar cross-bedding in lithofacies Sp. This element found associate with element CH because of channel migration. This element indicates a sandy bedform, which is a channel bed or may occur as a minor bar.

3) Element GB: Gravel bar bedform

In this area, gravel bar bedform (GB) is normally found as a channel bed. Sometime this element shows the channel migration as a result of erosional surface on the surface of underlying bed Gravel bar bedform at Samphanbok consist of thin bed of gravel in lithofacies Gm. This element indicates a gravel bar in the middle of channel.

Architectural formed on the overbank environment.

4) Element LS: laminated sand sheet

In this area laminated sand sheet (LS) compose of the thin bed of laminated fine-grained sandstone in lithofacies Sh. This element indicates the flash flood in the ephemeral river on the plain bed (Miall, 1977a). it may be gradually change from lithofacies St and Sp.

Table 4.4 The summary of architectural element and interpretation of the Samphanbok canyon modified from Miall (1985).

Element	Symbol	Principal lithofacies assemblage	Geometry and relationship
Channel	CH	Any combination	Concave up erosional base, internal concave up secondary erosional surface
Sandy bedform	SB	St, Sp, Sh	Channel fill, lens, sheet, minor bar
Gravel bar and bed form	GB	Gm	Lens, blanket
Laminated sand sheet	LS	Sh	Sheet, blanket

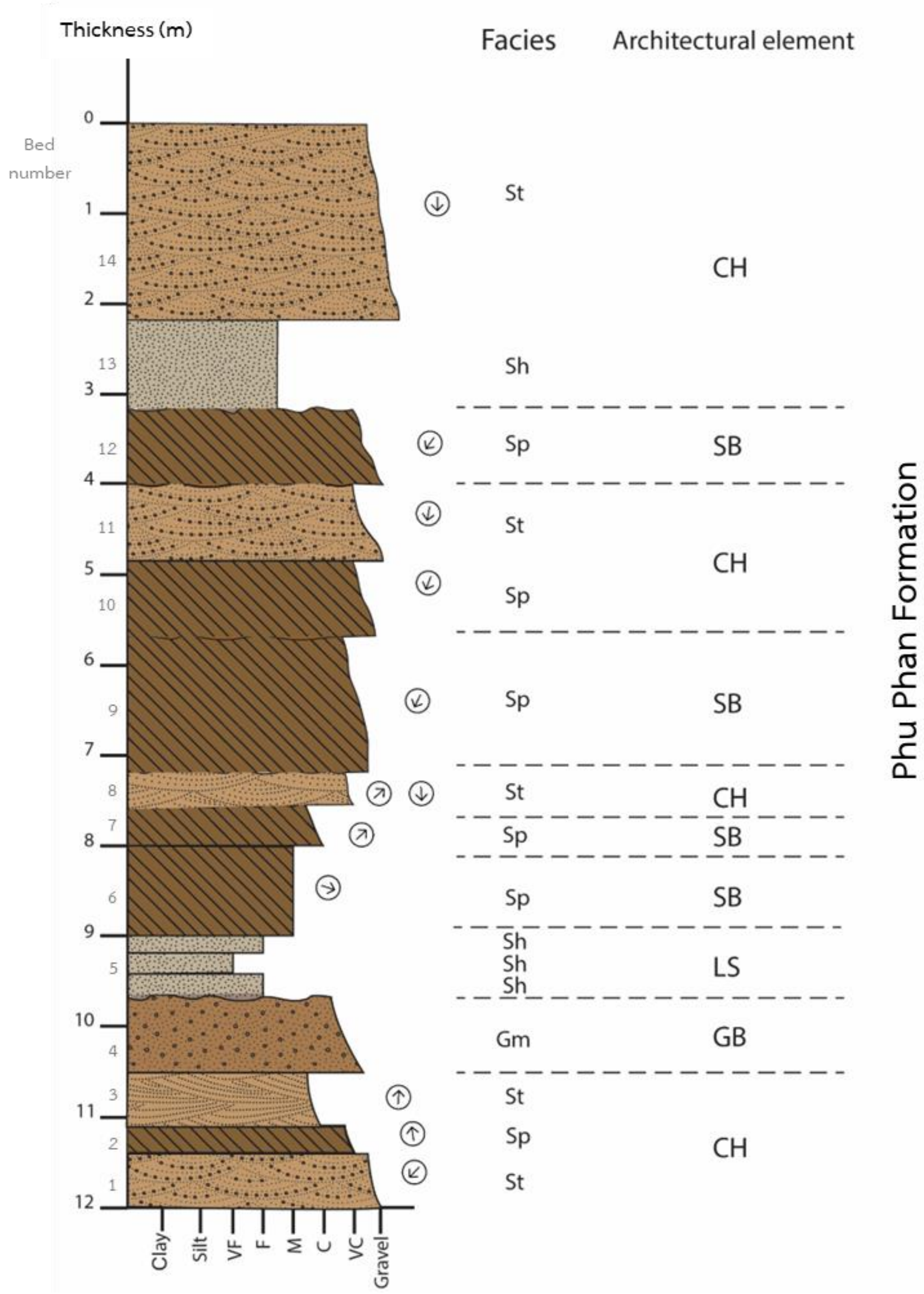


Figure 4.32 The stratigraphy with Paleo current of Phu Phan Formation at Samphanbok canyon.

4.5.5 Lithofacies of giant pedestal rock

The lithofacies from giant pedestal rock stratigraphy was classified by using the method from Miall (1977b, 1985) can be divide into three lithofacies. Such as sandy facies recognized by trough crossbedding (St), planar cross bedding (Sp) and horizontal lamination (Sh).

There are sand lithofacies associations for three lithofacies: gravel lithofacies, sand lithofacies, and fine-grained clastic facies. The specifics are provided below.

Association 1: sand lithofacies

1) Facie St: Trough cross-bedding

This facie is predominantly composed of the coarse to pebbly sandstone and some bed compose of medium to coarse sandstone with poorly sorted The major structure is trough cross-bedding. The thickness of this facie around 0.25-1.6 meters. This facies indicates the channel bed.

2) Facie Sp: Planar cross-bedding

This facie is predominantly composed of the medium to pebbly sandstone. The major structure is planar cross-bedding with poorly sorted. The thickness of this facie around 0.1-1 meters. This facies indicates the transverse and linguoid bar.

3) Facie Sh: Horizontal lamination

This facie composes of medium to gravelly sandstone. In this facie found the laminated sandstone with normal grading and poorly to moderate sorted. The thickness of this facie approximately 0.3-1.6 meters. This facies indicates the planar bed flow in the mega flood event.

Table 4.5 The summary of lithofacies and interpretation of the giant pedestal rock modified from Miall (1977a).

Facies code	**Lithofacies**	**Sedimentary structure**	**Interpretation**
	Sand lithofacies		
St	Sand, medium to v. coarse, may be pebble	Trough crossbedding	Dune, channel bed
Sp	Sand, medium to v. coarse, may be pebble	Planar crossbedding	Transverse and linguoid bar
Sh	Sand, fine to v. coarse, may be pebble	Horizontal lamination	Planar bed flow

4.5.6 Architectural element of giant pedestal rock

Based on Miall (1977b, 1985) these elements characterized by their geometries and bounded surfaces are used as a basis for interpreting the depositional environment. Three architectural elements were recognized: channel (CH), sandy bedform (SB), and laminated sand sheet (LS). The details of these architectural elements are described below.

Architectural formed in channel.

1) Element CH: Channel

In this area channel element (CH) compose of trough cross-bedding in lithofacies St, planar cross-bedding in lithofacies Sp, and lamination of lithofacies Sh. This element found associate with element SB because of channel migration. This element indicates as a channel that have a changing from riverbed to channel bar and flood plain.

2) Element SB: Sandy bedform

In this area, sandy bedform (SB) compose of trough cross-bedding in lithofacies St and planar cross-bedding in lithofacies Sp. This element found associate with element CH because of channel migration. This element indicates a sandy bedform, which is a channel bed or may occur as a minor bar.

Architectural formed on the overbank environment.

3) Element LS: laminated sand sheet

In this area laminated sand sheet (LS) compose of the thin bed of laminated fine-grained with normal grading sandstone in lithofacies Sh. This element indicates the flash flood in the ephemeral river on the plain bed (Miall, 1977a). it may be gradually change from lithofacies St and Sp.

Table 4.6 The summary of architectural element and interpretation of the giant pedestal rock modified from Miall (1985).

Element	**Symbol**	**Principal lithofacies assemblage**	**Geometry and relationship**
Channel	CH	Any combination	Concave up erosional base, internal concave up secondary erosional surface
Sandy bedform	SB	St, Sp, Sh	Channel fill, lens, sheet, minor bar
Laminated sand sheet	LS	Sh	Sheet, blanket

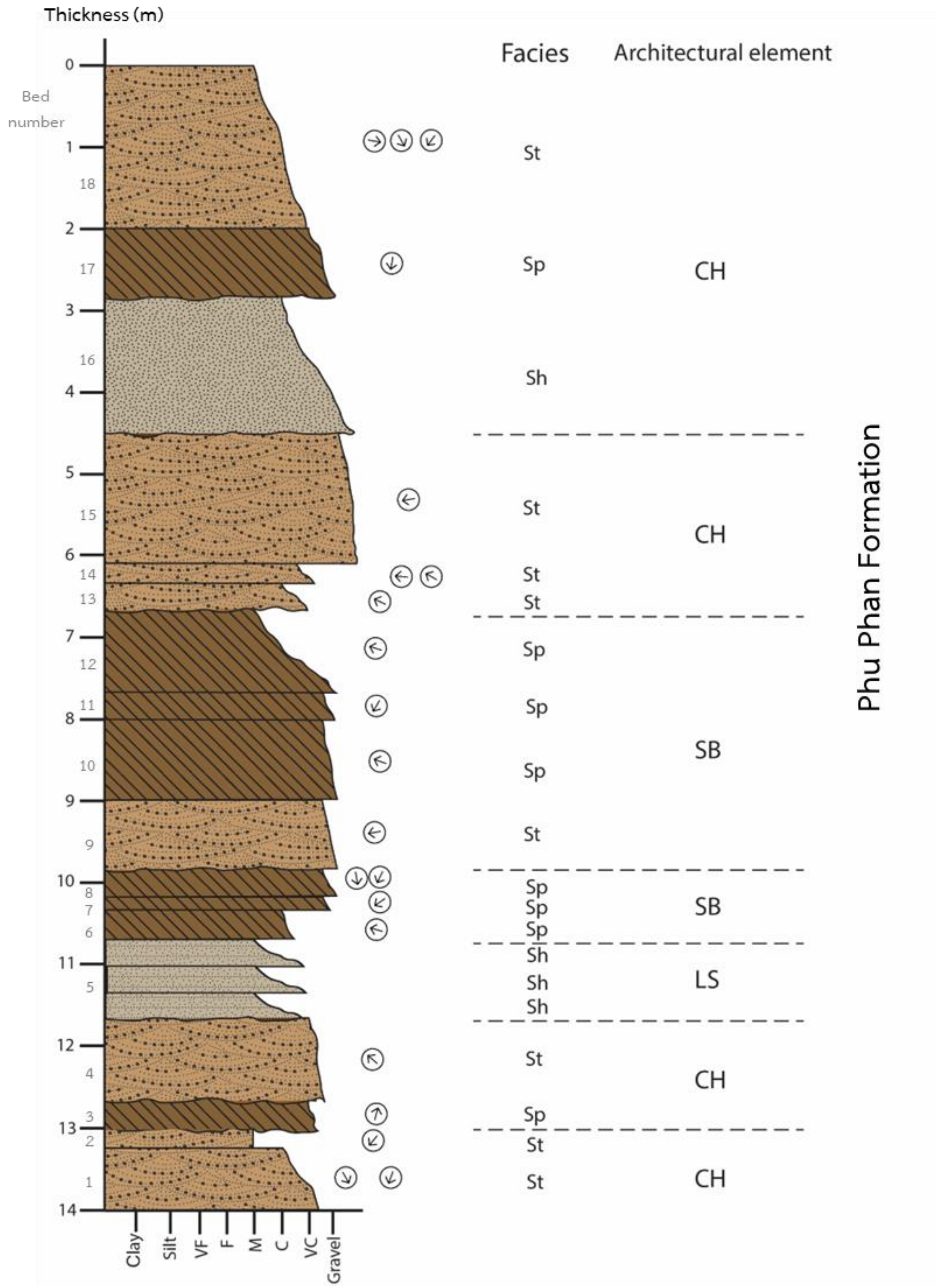
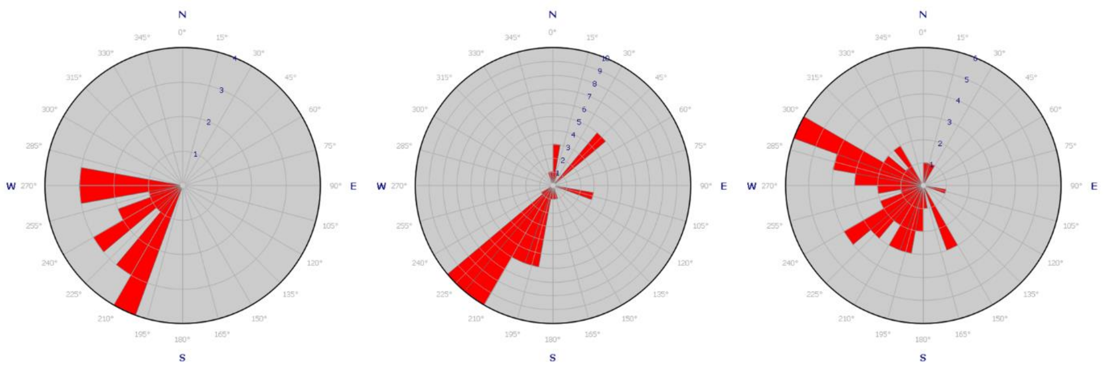


Figure 4.33 The stratigraphy with Paleo current of Phu Phan Formation at giant pedestal rock.

4.6 Paleocurrent

The Samphanbok area comprises two formations of Khorat Group sandstone, namely Phu Phan Formation and Sao Khua Formation, both of which were deposited in a fluvial environment. The sandstone in the fluvial environment is characterized by sedimentary structures such as planar cross-bedding and trough cross-bedding, which can indicate the direction of paleocurrents.

A total of 120 measurements of crossbedding were taken from three locations and represented on a rose diagram to determine the primary flow direction of the paleocurrent. Since the dip angle of the bedrock was less than 30 degrees, there was no need to correct for tectonic effects (Potter and Pettijohn, 1977; Tucker, 1988). At Ban Song Khon, where Sao Khua Formation and Phu Phan Formation contacted, 20 dip direction measurements were taken from the Phu Phan Formation sandstone because the Sao Khua Formation did not display crossbedding. The observed paleocurrent direction in this area was found to be towards the southwest. Similarly, at Samphanbok, where the Phu Phan Formation was present, 50 measurements of dip direction were taken, indicating that the primary flow direction of the paleocurrent was towards the southwest. Finally, in the Phu Phan Formation at the giant pedestal rock, 50 measurements of dip direction were obtained, showing that the primary flow direction of the paleocurrent was towards the west (Figure 4.33).



Ban Song Khon Samphanbok Giant pedestal rock

Figure 4.34 The rose diagram displays the paleocurrent direction from 120 data of dip direction from cross-bedding in the study area.

CHAPTER 5

DISCUSSION

5.1 Formation and Evolution of Potholes at Samphanbok

At Samphanbok, the sandstone beds are sub-horizontal to horizontal, which is one of the specific conditions that supports erosion on the surface of a riverbed, especially from the corrosion caused by grinders in a vortex current on top of the sandstone to subsequently form and enlarge the potholes (Fig. 5.1a). The vortex of local bedload grinders (Das, 2018) that predominantly consisting of granules, pebbles, and gravel derived from pebbly sandstone beds causes these potholes to expand over time (Fig. 5.1b). When rotating water and bedload sediments fall into a hole, a simple pothole expands, deepens, and opens up space for smaller potholes to scour inside it. Water flow during the rainy season also encourages the development of compound potholes within a large simple pothole (Figure 5.1c). Long-term pothole development at Samphanbok has likely led to the transition from simple to compound and hierarchical potholes. One of the indications that these features were formed over a long period of time is represented by the hierarchical (Figure 5.1d) and coalesced potholes (Figure 5.1e) at Samphanbok. The type of potholes can indicate the evolution of pothole which deepen and expand through the time (Figure 5.2)

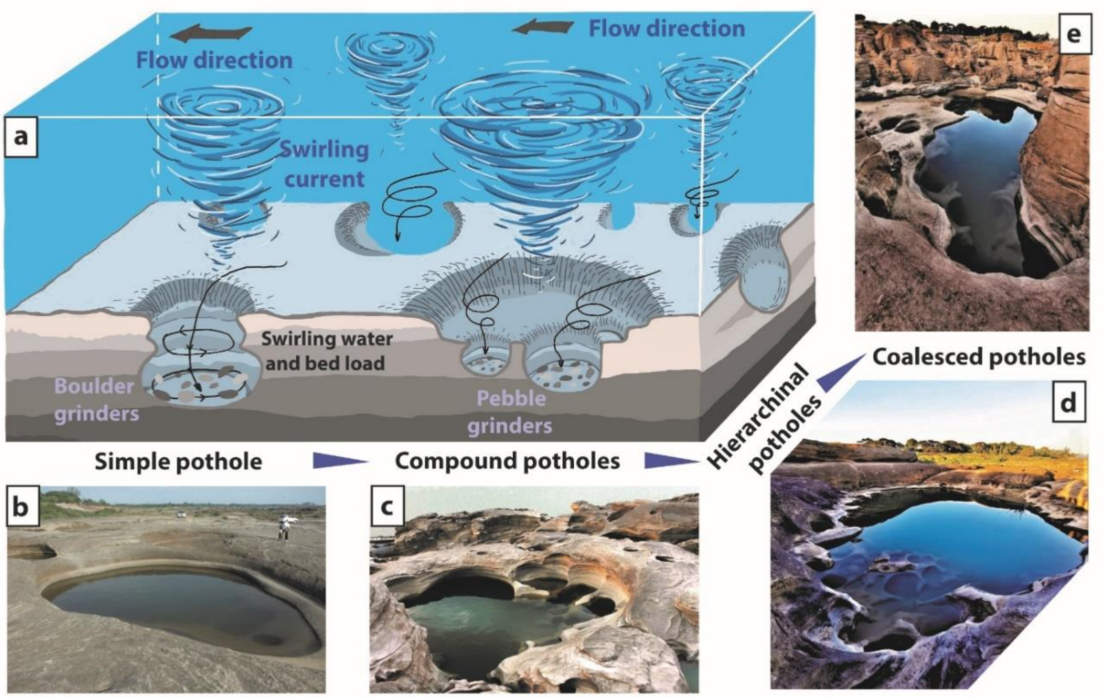


Figure 5.1 Idealized diagram showing the evolution of pothole at Samphanbok a) simplified form of several types of potholes generated by a swirling current b) Large simple ovoid shape. c) large compound potholes. d) Hierarchical potholes. e) Coalesced potholes (Udomsak et al., 2021).

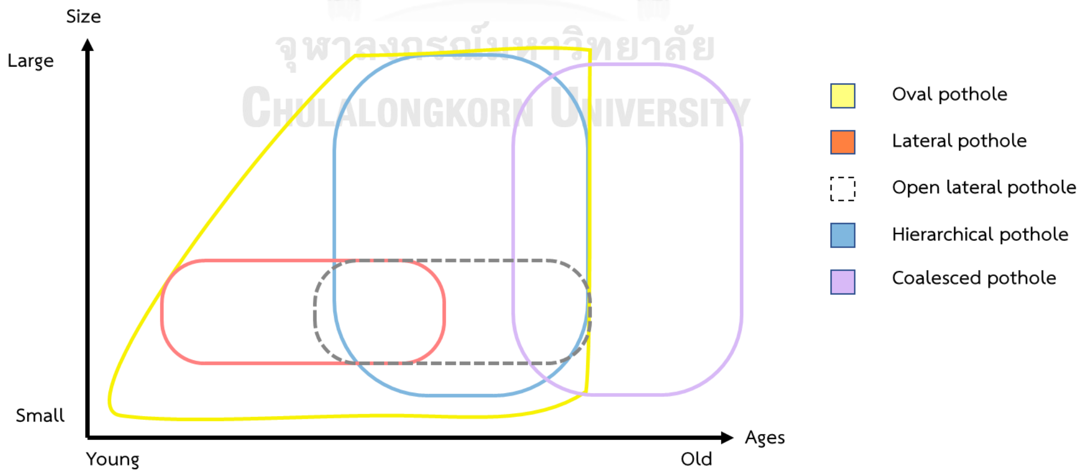


Figure 5.2 The diagram shows the pothole occurrence which relation between ages and size.

Sandstone beds of the Samphanbok potholes and Phachan tafoni fields were also part of the Phu Phan Formation, the Khorat Group (Choowong et al., 2013). During the Tertiary, when the Indian-Australian and Eurasia plates collided in the Himalayan orogeny, the Khorat Plateau was lifted and folded a lot (Booth and Sattayarak, 2011). The effect of a last collision on a regional scale was the folding of the sandstone beds. Both Samphanbok and Phachan are in the south-eastern part of the Phu Phan Range, where the Mekong River runs through a canyon. Erosional characteristics (i.e. potholes) as evidence of former riverbeds are left behind when the Mekong River cuts into the sandstone beds. It is assumed that, in general, potholes may have started occurring after the river started flowing after the uplifting occurred. There is no absolute dating available for when the Mekong River formed, but the occurrence of potholes in the top bed within the present bankfull elevation supports the river mechanism since the river began to develop. The evolution of the Mekong River today is a result of long-term vertical adjustment cutting into sandstone strata, making a deep canyon. The presence of potholes on each level of the sandstone bed is indicative of repeated long-term flooding at the bankfull elevation.

The width of the Mekong River at the bankfull level, measured from the bankfull limit in Thailand to the bankfull limit in Laos PDR, is between 1200 and 1300 m, while the width of the channel is between 100 and 300 m when the water level is maintained at a normal level of 20 m below the bankfull level. During the summer, the Mekong River's water level is slightly lower than normal, and the paleo-channels and sandstone beds are visible with almost dry potholes, with the exception of a few large coalesced and hierarchical potholes (Figure 5.3a). Within the bankfull elevation, the average summer daytime temperature is 35 °C, but can occasionally reach 40 °C, and falls to 25 °C at night. These varying daily temperatures at Samphanbok may cause surface weathering by thermal expansion. During the rainy season, the water level quickly rises due to the Mekong Basin's recharge and reaches the bankfull limit, turning the dry canyon and paleo-channel into the riverbed. During floods, the water velocity is generally faster and stronger than in the typical summer and winter. All potholes are submerged in water and re-sculpturing. Existing potholes may expand, connect, and erode, while new potholes may form (Figure 5.3b). The area covering the bankfull elevation is submerged for three to four months. Potholes in the middle sandstone beds and some potholes within the canyon are still active during the decreased water level and will quit forming when the water level returns to normal in winter (Figure 5.3c). The vortex on the surface of the water at a normal level reveals a dynamic, swirling current that generates different active potholes inside the current riverbed, and this cycle of pothole development occurs annually. Whether or not potholes will continue to occur relies on the Mekong River's water level, which is no longer predictable due to the construction of multiple dams upstream.

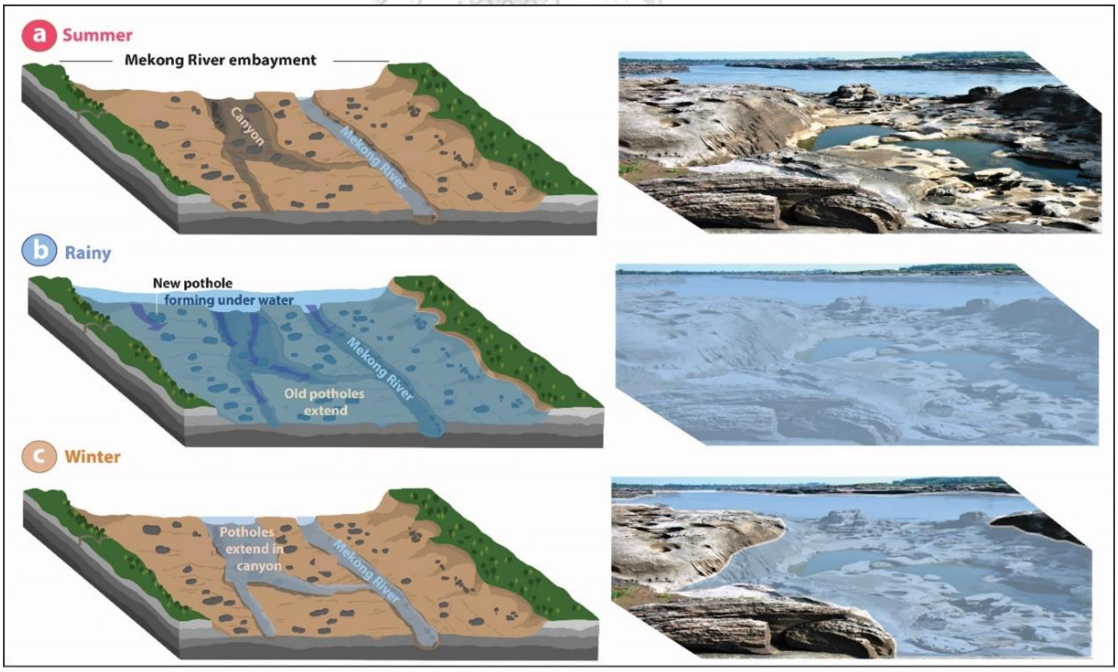


Figure 5.3 A simplified block evolution model of potholes at SPB during the different season of the year. a) The summer season is dry and hot climate. The water level in the Mekong River falls to its lowest level, and there is no flow of water within the canyon. In the recent Mekong riverbed, only

these potholes are active. b) The water level reached the bankfull level. All potholes in every sandstone bed are submerged, allowing for the formation of new potholes and the re-sculptured of existing potholes. c) After the rainy season, the water level in the canyon has decreased, but water continues to flow, causing the development of potholes in the canyon bed (Udomsak et al., 2021).

5.2 Simplified Formation of the Giant Pedestal Rock

The surface of the pedestal (twin stack) displays no indications of wind abrasion, suggesting that the pedestal bed has been degraded over time by water (rainwater and ancient river). Around the area of giant pedestal rock, there are potholes on the sandstone bed (Figure 5.4) in which the grinder inside is filled with sand sediment. The pothole has a width of approximately 10 - 50 centimeters and a depth of approximately 5 - 10 centimeters. Ji et al. (2018) named this pothole a hillside pothole, which is eroding in the direction of widening more than deepening. The grinders of hillside potholes are sand-sized sediments, which grind and erode at the rim more than they erode on the bottom by the gravity effect and are easy to wash out by running water.

Figure 5.4 The photo showing the hillside pothole in the giant pedestal area.

Sandstone beds that are hard horizontally are generally difficult to erode (Figure 5.5a). Intriguingly, the fractures discovered between the twin pedestal stacks bisected not only the pedestal rock but also a cap rock. It is evident that regional tectonic uplift or folding could have caused these vertical fractures in the horizontal bed sandstone. In order to form a syncline, the sandstone beds where the giant pedestal rock is located may have been uplifted. This uplift, possibly the effect of concave folding, resulted in the vertical uplift (cracks and fractures) of the sandstone beds. Then, differential weathering and erosion occurred, with a more durable cap rock on top of a layer with less resistance (Figure 5.5b). The thin base of a balanced rock is typically formed of soft sedimentary material that is not as resistant to disintegration or erosion as the more resistant upper layers (cap rock) of the rock mass. The long-term degradation process and a number of ancient gullies have formed and carried sediments from the back slope to the main river, which is currently probably the Mekong River (Figure 5.5c). The morphology of the pedestal rock and cap rock remnants on the ground surface (Figure 5.5c) are the result of long-term geological evolution from the last regional tectonic activity. On the Khorat Plateau, remarkable giant pedestal rocks are also observed (Figure 5.5c).

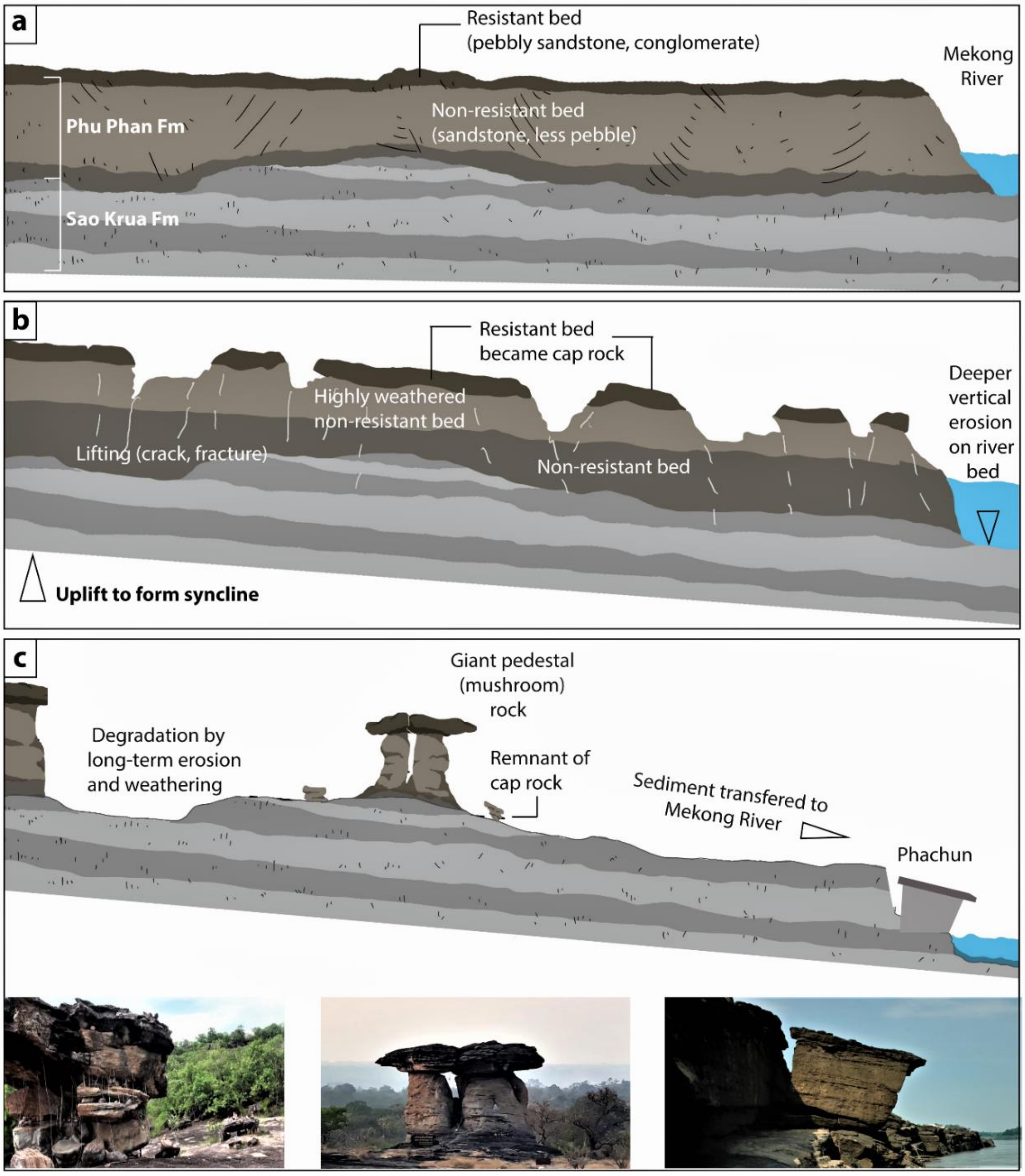


Figure 5.5 Simplified evolution of the giant pedestal rock through time. a) The Phu Phan Formation's original geographical features consisted of resistant and non-resistant beds. The uppermost bed is composed of pebbly and conglomeratic sandstone that is thick and massive. The several beds below consist of coarse-grained sandstone that is less resistant than upper bed. b) Lifting (cracks and fractures) occurred as a result of the regional tectonic collision during the lifting of all rock formations. The Phu

Phan Range's folding is composed of large vertical fractures. The resistant bed was eroded and weathered to a lesser than the non-resistant bed below. c) The sediment on the back slope of the Mekong River was removed due to long-term erosion. There were still some remnants of the resistant bed on the ground. Only one giant pedestal rock with a vertical crack was preserved. In addition, rock falls were seen in Phachun (Udomsak et al., 2021).

5.3 Mechanism of Pothole Evolution

5.3.1 Relation between the Pothole Occurrence and Geological Structure

Potholes are a common erosional feature found in river bedrock, particularly in rivers with high energy. However, it is rare to come across a large number of potholes in a single location, and the surrounding area typically does not resemble the unique potholes found at Samphanbok.

At Samphanbok, there is a density of particularly unique potholes, which are of varying shapes and sizes. Some are deep cylindrical holes, while others are shallow and wide depressions. These potholes are believed to have formed over a long period of time, through the erosive power of water and sediment.

The location of Samphanbok is situated in the middle of a syncline where the bedrock is nearly horizontal. The Mekong River flows through this area, and sediment in the water erodes every face and fracture of the bedrock, resulting in the formation of potholes across the region. Towards the north of the Samphanbok area, there are several canyons in the Mekong River, which constrict the river and cause it to become narrow. At Ban Son Khon, the narrowest point of the Mekong River (Figure5.6), which is only 40 meters wide, the flow velocity and water level increase due to the constriction of the river (Wang et al., 2016).

Furthermore, Samphanbok is located in the cut bank zone, which is an area with the highest rate of erosion (Figure 5.7). This is because the river's velocity and energy are concentrated on one side of the bank, leading to greater erosion and pothole formation. All of these factors, including the syncline's horizontal bedrock, the canyons, the narrowness of the river, and the cut bank zone, have contributed to the formation of thousands of potholes in this single location.

The unique geological conditions of Samphanbok have resulted in the creation of a breathtaking landscape that attracts visitors from far and wide. The numerous potholes, each with their own unique shape and size, are a testament to the power of nature and the fascinating ways in which it can shape the earth's surface over time.

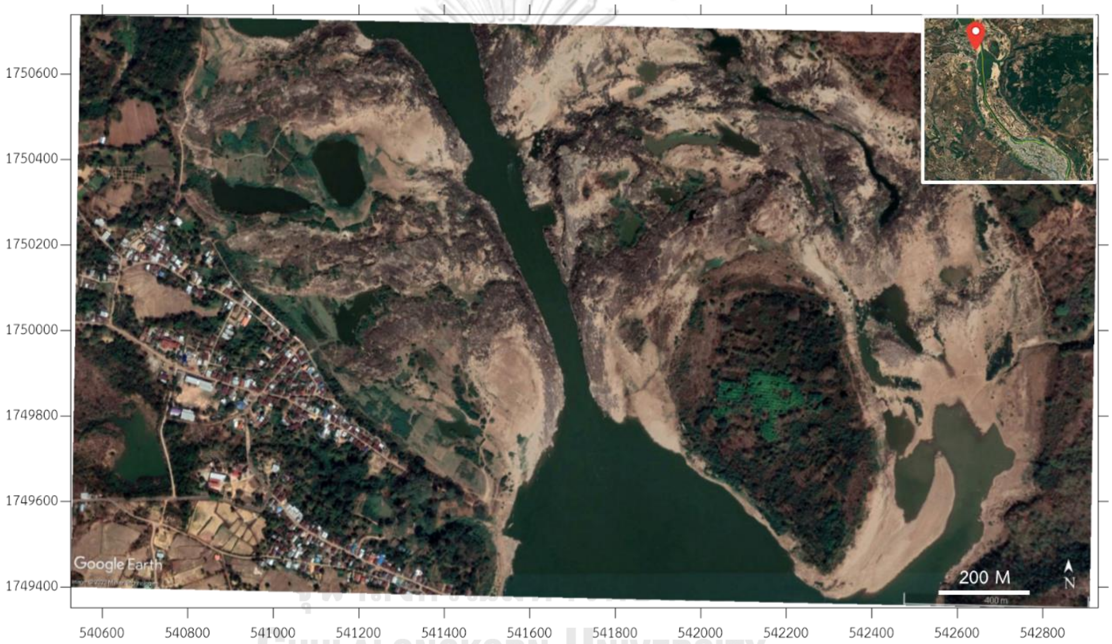


Figure 5.6 The photo from the satellite image displays the narrowest point of Mekong river at Ban Song Khon.

Figure 5.7 The satellite image from Google Earth overlay by the ariel photo from drone showing the Samphanbok locate in the cut bank zone.

5.3.2 Relation between the Pothole Occurrence and Lithology

The occurrence of potholes in Samphanbok is determined by the lithology of the sandstone. To investigate this relationship, the northern area of Samphanbok was selected because of its lower pothole density and greater interpretability. Potholes in this region typically take the form of single, compound, or hierarchical structures and are larger than 2 meters in size. These potholes are mainly found in sandstone formations characterized by planar cross-bedding, with larger potholes being typically single in nature (Figure 5.8). On the other hand, potholes that appear in sandstone formations composed of trough cross-bedding are typically smaller in size but spread out across the surface (Figure 5.9). Planar cross-bedded sandstone is more homogeneous than trough cross-bedded sandstone, which is characterized by a lobe shape and generates weak points throughout the surface. Single, large potholes are the result of the same erosional rate in homogeneous sandstone. Interestingly, hierarchical potholes in this area occur in two connected layers of sedimentary structures. Initially, potholes start as single structures in planar cross-bedded sandstone but widen and deepen until they erode through to the trough cross-bedded sandstone layer. In the trough cross-bedded sandstone layer, potholes appear as secondary features at multiple weak points on the surface and exhibit the characteristics of hierarchical potholes (Figure 5.10).

In addition, the grinder in the Samphanbok area plays a significant role in determining the typology of potholes. The grinder is responsible for eroding the walls and floors of the potholes, and is derived from the sandstone bed. As pebbles from the upper bed fall into the grinder, the volume of pebbles in the grinder increases. Near the water level of the Mekong river in the lower bed of Samphanbok, hierarchical and coalesced potholes are prevalent due to the high volume of pebbles inside these potholes, indicating a high rate of erosion. Additionally, potholes at this level are often submerged in the Mekong river, further increasing the erosional rate and causing potholes to erode and connect to form coalesced potholes.

Figure 5.8 The photo showing the single pothole occur in the bed of planar cross-bedding.

Figure 5.9 The photo show the smaller pothole, which occur in the bed of trough cross-bedding, inside the large pothole.

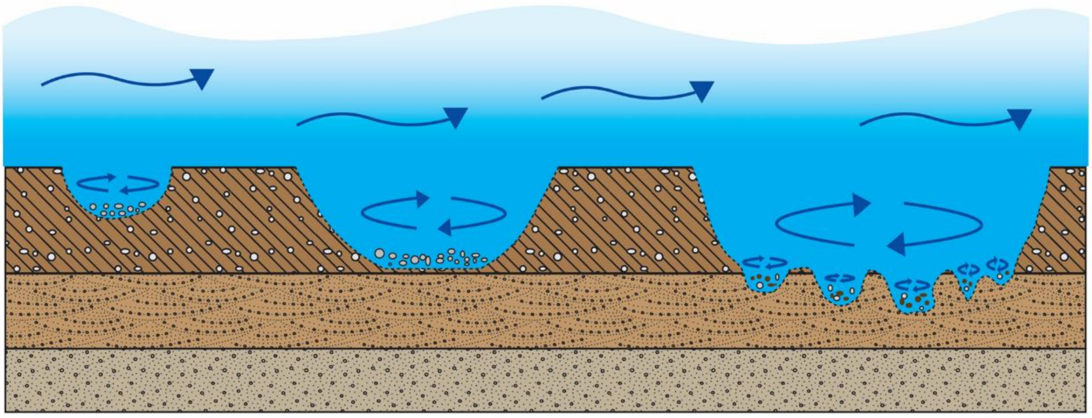


Figure 5.10 The illustrate show the evolution of hierarchical pothole at Samphanbok.

5.4 Paleo Environment

The study area exhibits five architectural elements of a depositional system, comprising CH, SB, and GB as channel fills, and LS and OF as overbank deposits. At Ban Song Khon, the contact between the Sao Khua Formation and Phu Phan Formation can be observed. In the section of the Sao Khua Formation, the lithology displays fine-grained deposits, which are interpreted as a fine lamination facies (Fl) and fine massive facies (Fm), representing the overbank deposit in the form of a sheet flood and paleochannel fill. These two facies can be grouped as the overbank fine (OF) architectural element, which indicates the depositional environment during a flooding event that flowed over the levee and onto the flood plain, similar to a sheet flow. Additionally, calcrete can be found on top of the sandstone bed in the Sao Khua section. Calcrete refers to a type of sedimentary rock or soil that is composed mainly of calcium carbonate ($CaCO3$), which has precipitated from groundwater in arid or semi-arid regions. It forms as a result of the concentration of dissolved calcium carbonate in the groundwater due to the high rates of evaporation and the lack of precipitation in such regions. There is no indication of cross-strata in the Sao Khua Formation within the study area, which suggests that the calcrete is in situ and not transported by fluvial processes. The paleoenvironment of this section is the floodplain with the semi-arid climate by the evidence of calcrete.

The Phu Phan Formation, located in three different sites, namely Ban Song Khon, Samphanbok, and giant pedestal rock, is composed of four main architectural elements that include channel (CH), Sandy bedform (SB), gravel bar and bed form (GB), which are defined as a channel depositional environment, while the Laminated sand sheet (LS) is defined as an overbank depositional environment. The Channel (CH) element in the study area is made up of facies Sp St, and some beds also include Sh and Gm facies (Figure 5.11). Facies St indicates dunes and channel beds, while facies St indicates transverse and linguoid bars. Sometimes, Gm facies, which indicates the presence of gravel bars in the river, and Sh facies, which indicates planar bed flow that deposits during mega flood events on the floodplain, are also observed in this element. The Sandy bedform (SB) element in the study area mainly comprises Sp and Sh facies that indicate the presence of sandbars and lateral accretion. The Gravel bar bedform (GB) mainly consists of Gm facies that indicate the presence of gravel bars in the middle of the channel. The last architectural element, Laminated sand sheet (LS), is composed only of Sh facies, indicating the occurrence of mega flood events.

Based on the different architectural elements present in the study area, the Phu Phan Formation was formed in a channelized river system with a variety of depositional environments. The Channel (CH) element played a key role in creating dunes and channel beds, while the Sandy bedform (SB) and Gravel bar bedform (GB) elements indicate the presence of sandbars, lateral accretion, and gravel bars within the river. The Laminated sand sheet (LS) element further suggests that the formation was affected by mega flood events, which resulted in overbank deposition.

The bedrock in Samphanbok area can be refer to the stratigraphic column in the study area (Figure 4.19). The lithology of this area almost composes of pebbly sandstone with planar and trough crossbedding. Trough crossbedding is indicator of the current flow in the multiple direction, in this area they indicate the multiple channels in the river. Moreover, in the stratigraphic column show the gravel beds which related to the gravel bar not only common in the braided river but also indicate the high flow energy. Small grain size bed is rarely to find in this area that mean overbank flow and floodplain are not dominated in study area.

It can be inferred that the river had high enough energy to transport the gravel and deposit it in the gravel bars, while the trough cross-bedding is indicative of multiple channels. The minor floodplain indicates that the river was likely braided river, with local paleocurrent flow in the west and southwest directions (Figure 5.12).

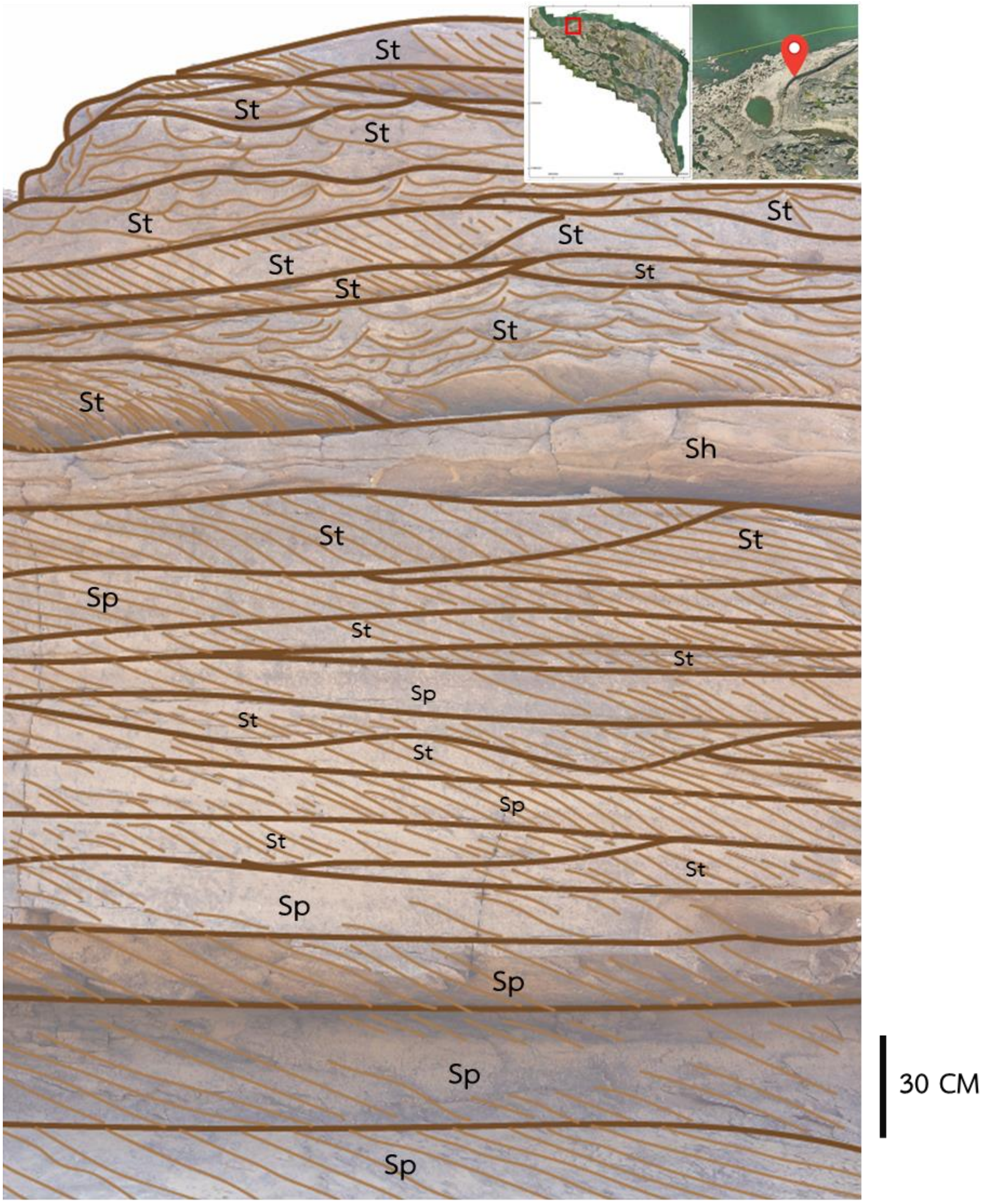


Figure 5.11 The photo shows the lithofacies in the Phu Phan formation sandstone at the Samphanbok. Sp facies show sandstone with planar crossbedding and St facies show sandstone with trough crossbedding.

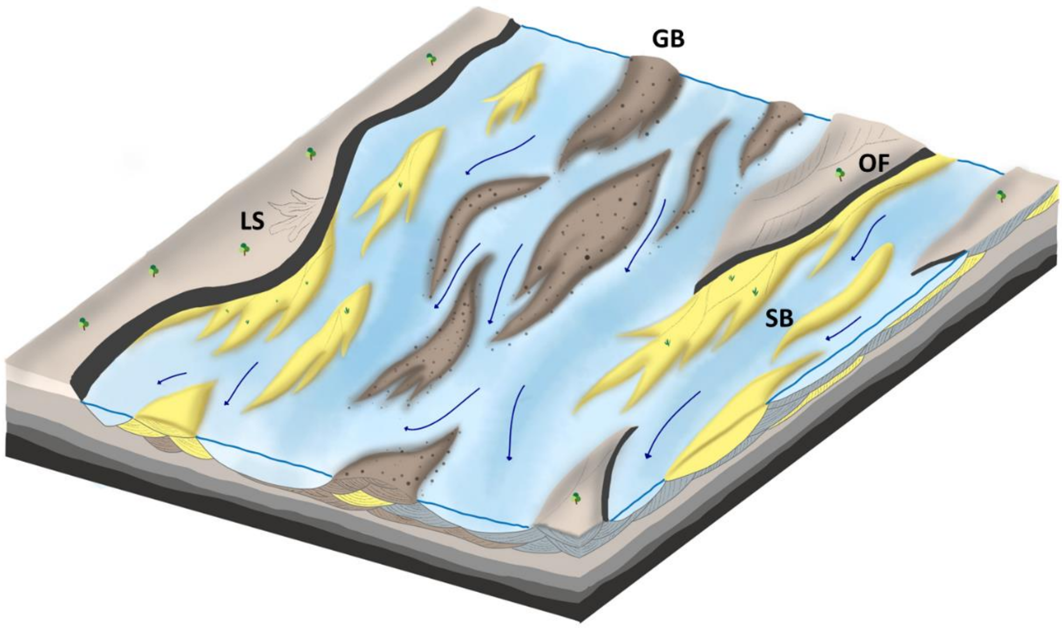


Figure 5.12 The illustrate displaying the paleoenvironment of Phu Phan Formation sandstone in Early Cretaceous interpret from the architectural element.

5.5 Potential for Samphanbok as a Global Geological Heritage Site

Based on a multi-level analysis of the relief, Sellier (2010) developed a deductive integrated approach for the selection of an appropriate scale of geomorphosites for education and tourism in the context of geomorphology and geology education. As a result, an integrated approach to evaluating Samphanbok is introduced in this dissertation as follows. Beginning with the definition of the main characteristics of the area under consideration, i.e., the diversity of the thousands of potholes, which defined and characterized the key geomorphological components of broadly similar large dimensions, but different characteristics based on their topographical, structural, and sedimentological features. The subdivision of pothole components into several types of comparable dimensions was completed. This approach is advantageous because the selected Geological heritage sites provide an overview of the geology of the studied area.

In this dissertation, rarity is offered as an important criterion for evaluating the scientific significance of Samphanbok. Rareness refers to the rarity of a location relative to a reference space, such as a region, commune, or country (Reynard et al., 2007). Though potholes are common erosional features on a riverbed, the development of thousands of potholes in the same location is impressive, indicating that this site is significant. In addition, the largest and tallest pedestal (mushroom) rock in the country is located in Samphanbok, and there is no evidence of wind erosion at this site.

5.6 Preparation for Education and Tourism

For educational purposes, the site's potential should be qualitatively documented. At the university level, sedimentological studies explaining the mechanical formation of the thousands of potholes at Samphanbok are still lacking in detail. Nonetheless, information for other educational stages is essential. Good cartographic representation is essential for communicating the results (Coratza and Regolini-Bissig, 2009), particularly to the stakeholders (public authorities, decisionmakers, and park managers) and non-geoscientists (Marchetti, Coratza, and Carton, 2005). The maps presented in this dissertation were used at two levels: (i) at the level of the Geological heritage site, as part of the assessment procedure, and (ii) at the regional scale, as a tool for the synthesis of the results. For the assessment phase, a complete coverage of the studied area with a geomorphological map is required, but this can be time-consuming for large areas (Reynard et al., 2015). Therefore, in this dissertation utilised simplified geological and geomorphological maps as well as diagrams that depict the site's episodic evolution.

As a requirement for the tourism in general, all existing interpretive data in this dissertation are complete and appropriately documented. As a requirement for the tourism in general, all existing interpretive data in this dissertation are complete and appropriately documented. However, they should be concerned with producing both in situ (such as panels) and ex situ (such as booklets, websites, flyers, virtual visits, etc.) facilities in addition to guided tours at a provincial or community level (Reynard et al., 2015). At present, the local governors in Samphanbok have already launched several ex-situ facilities and trained local students as tour guides. Therefore, a more extensive transfer of geological knowledge to these students is required.

5.7 Simplified Risk Management

To meet all of the requirements of a Geological heritage site, the usage of Geological heritage sites described in this section by society and tourists aims to characterize the site in terms of its protection and/or promotion. The protection of the site should be well organized by local communities and should be documented using the two criteria of (i) the protection status and (ii) the damages and threats. It may include legal protection (protected site) and/or physical protection, such as the existence of fencing (Reynard et al., 2015). It can also relate to the location where erosional processes are predictable.

The cause of damage to potholes in Samphanbok Geological Heritage Sites is not commonly detected on or within the site itself. Based on the geomorphological conditions of the site, the damage should be considered in relation to fluvial environments. As a result of river damming, there is a potential that the site will be harmed. Over the Mekong River, both upstream and downstream of the Thai-Laos PDR border, a number of dams are being built for electricity and irrigation purposes. Clearly, dams change the river's flow capacity and reduce sediment transfer downstream. Due to rainwater recharge from upstream and the nearby sub-catchment, the Mekong River at the study area only maintains a natural bankfull condition during the rainy season (September to November). This seasonal bankfull encourages the development of all active potholes, even in the sandstone bed with the highest elevation within the bankfull elevation. This bankfull condition also concerns the sandstone bed's stability. Some fractures may form during flooding and after the rainy season, where the breakdown of rock stability might result in rock fall. Within the canyon, the possibility of a rockfall exists (Fig. 5.13a). The reduced risk at the Samphanbok Geological Heritage Sites still needs to be taken to consideration, particularly what will happen in the case of a long-term drought caused by climate change. Any long-term drought will stop all exposed pothole formation and cause the rock surfaces to fracture as a result of thermal expansion. The effect of thermal expansion on the top of the sandstone bed already happens every year when the seasons change. It also affects the highly weathered mega crossbedding that surrounds the lower part of the active pothole bed. When the bed's relief from the normal water level is less than 1 m, erosion is more likely to occur than in the other beds above it. This lower sandstone bed may be eroded, making it unstable, and the upper beds may be at risk of sudden collapse (Figure. 5.1 3b). A large hierarchical pothole represents the last risk for tourists. This swimming pool-like pothole is inviting for jumping. The majority of large pools we surveyed over the summer were shallow, and some contained many small potholes (Figure 5.1 3c). Inside a pool, jumping or swimming should be restricted. The quality of the water within a pool may not satisfy the standard for drinking, hence its usage for any purpose should be forbidden.

Figure 5.13 The picture shows the risk area in the Samphanbok area. a) Locations of potential rock falls and collapses within the famous canyon. b) In place of a steep bedding-plane inclination, slippery rock can also occur during the rainy season. c) the shallow hierarchical pothole that risk to jump into it (Udomsak et al., 2021).

CHAPTER 6
CONCLUSION

Sam Phan Bok, also known as the "Grand Canyon of Thailand", is situated in the Mekong River in Ubon Ratchathani province, in the northeastern part of Thailand. It is a vast area of rock formations that have been shaped by sediment in the vortex currents of the river over time, creating an otherworldly landscape of holes.

6.1 Typology of pothole

The potholes found at Samphanbok can be classified into two main groups: structure control potholes and non-structure control potholes. The structure control potholes are caused by the formation's joints and fractures, and they can coalesce over time to create larger formations due to erosional processes. On the other hand, non-structure control potholes occur on the surface and can be classified into five types.

The first type is the ovoid pothole, which is the initial stage of pothole formation and can expand to connect with other potholes, forming shapes like the iconic Mickey Mouse. The second type is the lateral pothole, which is found on the side wall of the channel. The third type is the open lateral pothole, which occurs when the rim and floor of the lateral pothole erode and become open to the channel's side. The fourth type is the hierarchical pothole, which resembles a large pond with smaller potholes forming secondary sculptures within it. The most well-known hierarchical pothole at Samphanbok is called "Sra Morakot" and is the largest of its kind. Finally, the coalesced pothole is the last stage of pothole formation when it continues to erode and connect with other potholes until it no longer resembles a pothole at all (Figure 6.1).

Mechanism of Pothole Evolution						
Factor Controlled \ Typology		Ovoid pothole	Lateral pothole	Open lateral pothole	Hierarchical pothole	Coalesced pothole
Structure	Non-structure control	✓	✓	✓	✓	✓
	Structure control	✓			✓	✓
Age	Young	✓	✓			
	Middle	✓	✓	✓	✓	
	Old	✓		✓	✓	✓
Location	Top bed	✓				
	Middle bed	✓			✓	✓
	Bottom bed	✓			✓	✓
	Channel rim	✓	✓	✓		
Sedimentary structure	Planar crossbedding	✓	✓	✓	✓	✓
	Trough cross-bedding	✓	✓	✓		✓
Grinder	Low	✓	✓	✓		
	High	✓			✓	✓

Figure 6.1 The mechanism of pothole evolution shows the relation between typology and factor controlled of pothole.

6.2 Potholes Formation

At Samphanbok, sub-horizontal to horizontal sandstone beds support erosion on the riverbed surface, particularly from vortex current corrosion caused by grinders made up of granules, pebbles, and gravel.

The formation and evolution of potholes involve several stages. Initially, the process begins with the flow of water entering joints or fractures in the rock surface, gradually eroding it over time. This erosion takes place through a grinding action, resulting in the formation of ovoid-shaped potholes. These ovoid potholes represent the first stage of pothole evolution.

As the ovoid potholes continue to erode and enlarge, they may merge with other ovoid potholes, forming compound potholes. This marks the second stage of pothole evolution. With further expansion, the compound potholes create enough space for secondary potholes to occur within them, resulting in the formation of hierarchical potholes.

In the final stage of pothole evolution, the potholes undergo further erosion and connectivity. Their walls erode, leading to the formation of coalesced potholes. Coalesced potholes represent the last stage of pothole evolution, where multiple potholes are interconnected.

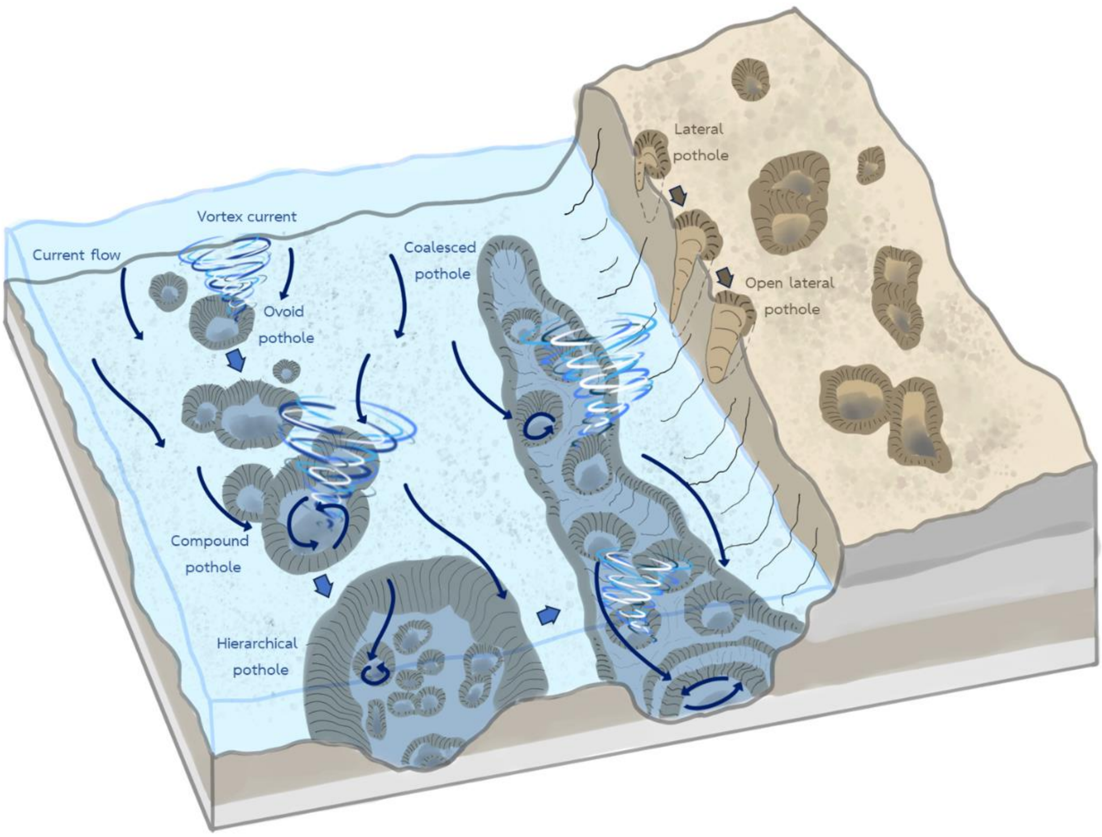


Figure 6.2 The illustrate showing the evolution of pothole from the ovoid potholes erode and expand to coalesced potholes.

The sandstone beds of Samphanbok and Phachan tafoni fields are part of the Phu Phan Formation, which was folded during the Tertiary due to the Indian-Australian and Eurasia plates' collision in the Himalayan orogeny. Potholes serve as evidence of former riverbeds left behind as the Mekong River cuts into sandstone beds. The river's evolution over time has resulted in the deep canyon observed today, and the presence of potholes on each level of the sandstone bed suggests repeated long-term flooding at the bankfull elevation. Temperature fluctuations at Samphanbok may cause surface weathering by thermal expansion, and the Mekong River's water level fluctuations during rainy and dry seasons cause potholes to erode and form annually. However, the construction of dams upstream makes it difficult to predict future pothole formation.

6.3 Giant Pedestal Rock Formation

The giant pedestal rock is the mushroom like rock located near the Phachan cliff, 1 kilometer from the Mekong River. The giant pedestal rock is the largest pedestal rock in Thailand. it is the result of the differential erosion of the bedrock. The cap rock is composed of the basal conglomerate bed is more resistant to erode than the balance rock. The pedestal on the twin stack doesn't seem to have been affected by wind abrasion, indicating that the pedestal bed has been degraded by water over time, specifically rainwater and an ancient river. Near the giant pedestal rock, there are potholes on the sandstone bed that have grinders filled with sand sediment. These potholes are called hillside potholes and erode more in width than depth. The fractures discovered between the twin pedestal stacks bisected not only the pedestal rock but also a cap rock, and these vertical fractures in the horizontal bed sandstone may have been caused by regional tectonic uplift or folding. The sandstone beds where the giant pedestal rock is located may have been uplifted to form a syncline, resulting in differential weathering and erosion, with a more durable cap rock on top of a layer with less resistance. The thin base of a balanced rock is typically formed of soft sedimentary material that is not as resistant to disintegration or erosion as the more resistant upper layers. Long-term degradation processes and ancient gullies have formed and carried sediments from the back slope to the main river, which is currently believed to be the Mekong River. The morphology of the pedestal rock and cap rock remnants on the ground surface are the result of long-term geological evolution from the last regional tectonic activity. Similar giant pedestal rocks are also observed on the Khorat Plateau.

6.4 Other Erosional Remnant at Samphanbok Area

The Samphunbok area at the Phachan cliff has weathered holes called "Sam Muan Roo" that resemble tafoni features. Tafoni is a landform formed by weathering of acid to intermediate plutonic rocks and is usually found in semiarid climates. The origin of tafoni in granite is controversial, and instead of being the result of salt crystallization, the tafoni at Samphunbok may have formed as a secondary deposit. In addition to the potholes, other erosional features were found in the lower sandstone bed of the Samphunbok area, including pedestal mounds with a pebbly sandstone coating, brain-like rocks formed from thermal expansion and water corrosion, and natural arches or pillars formed from breached and coalesced potholes.

6.5 Factor Controlled of Potholes Occurrence

Samphanbok is a location known for its density of unique potholes of varying shapes and sizes, which were formed over a long period of time through the erosive power of water and sediment. The location is situated in the middle of a syncline with nearly horizontal bedrock, where the Mekong River flows and erodes every face and fracture of the bedrock. The area also has several canyons in the Mekong River towards its north, which cause the river to become narrow and increase its flow velocity and water level at Ban Song Khon, the narrowest point of the river. Additionally, Samphanbok is located in the cut bank zone, an area with the highest rate of erosion, leading to greater erosion and pothole formation. All of these factors have contributed to the formation of thousands of potholes in this single location, creating a breathtaking landscape that attracts visitors from far and wide.

The lithology of sandstone and the grinder in Samphanbok contribute to the formation and typology of potholes. Potholes in planar cross-bedded sandstone are larger and single, while those in trough cross-bedded sandstone are smaller and more spread out. Hierarchical potholes occur in two connected layers of sedimentary structures. The grinder, derived from the sandstone bed, erodes the walls and floors of the potholes and increases erosional rate. Hierarchical and coalesced potholes are prevalent near the water level of the Mekong River, indicating a high rate of erosion.

6.6 Paleoenvironment of Sandstone at Samphanbok

The study area consists of five architectural elements representing a depositional system, including channel fills (CH), over bank deposits (OF), and gravel bars (GB), among others. The Sao Khua Formation displays fine-grained deposits interpreted as overbank deposits in the form of a sheet flood and paleochannel fill. Calcrete on top of the sandstone bed suggests a semi-arid climate floodplain. The Phu Phan Formation includes four main architectural elements, indicating a channelized river system with sandbars, gravel bars, and lateral accretion. The presence of mega flood events is indicated by the Laminated sand sheet (LS) element. The river likely had high energy and was braided with local paleocurrent flow in the west and southwest directions.

6.7 The Significant of Samphanbok to Promote to Global Geoheritage Site

Samphanbok, a natural site in Thailand, has been proposed as a geological heritage site for its rare potholes and rock formations. A multi-level analysis of the relief was used to evaluate the scientific significance of the area, and rarity was offered as an important criterion. To prepare for education and tourism, good cartographic representation is essential, and interpretive data should be complete and appropriately documented. To meet the requirements of a geological heritage site, the protection and/or promotion of the site should be well-organized and documented using criteria such as the protection status and damages and threats. Additionally, geological heritage sites should be protected and documented by local communities, using protection and damage criteria. Damage to the Samphanbok Geological Heritage Sites is related to fluvial environments and potential harm from river damming. A long-term drought caused by climate change could also cause instability and rock fall. Tourists should be aware of the risks posed by large hierarchical potholes and restricted from jumping or swimming in them, as the water quality may not be suitable for any purpose.

REFERENCES

Alexander, H. S. 1932. Pothole erosion. The Journal of Geology 40: 305-337.

Allen, J. R. L. 1983. Studies in fluviatile sedimentation: Bars, bar-complexes and sandstone sheets (low-sinuosity braided streams) in the brownstones (L. devonian), welsh borders. Sedimentary Geology 33: 237-293.

Álvarez Vázquez, M. Á., and De Uña-Álvarez, E. 2017. Growth of Sculpted Forms in Bedrock Channels (Mino River, Northwest Spain). Current science 112: 996-1002.

Blackwelder, E. 1909. Cenozoic History of the Laramie Region, Wyoming. The Journal of Geology 17(5): 429-444.

Blank, H. R. 1958. Pothole grooves in the bed of the James River, Mason County, Texas. Texas Journal of Science 10: 293-301.

Booth, J., and Sattayarak, N. 2011. Subsurface Carboniferous-Cretaceous geology of NE Thailand. The Geology of Thailand: 185-222.

Bryan, K. 1926. Pedestal rocks formed by differential erosion. US. Geological Survey Bulletin 790: 1-15.

Chenrai, P. 2011. Paleocurrent Analysis of the Sao Khua Formation, Khorat Group, Nong Bua Lamphu region, NE Thailand. Arabian Journal for Science and Engineering 37(1): 115-120.

Choowong, M. 2011. Basic geomorphology. Phra Nakhon Si Ayutthaya: Tienwattana Printing.

Choowong, M., Charoentitirat, T., Chutakositkanon, V., Pailoplee, S., and Phantuwongraj, S. 2013. In-depth Research of Significant Geological Data for Establishing the Geo-park Conservation. Final report of Chula Unisearch submitted to Department of Mineral Resources: 101.

Chua, S., Lu, X. X., Oeurng, C., Sok, T., and Grundy-Warr, C. 2021. Drastic decline of floodpulse in the Cambodian floodplains (the Mekong River and the Tonle Sap system).

Chuaviroj, S. Deformmation of Khorat Plateau, Thailand. In P. Dheeradilok, C. Hinthong, P. Chaodumrong, W. Tansathien, C. Utha-Aroon, N. Sattayarak, T.

Nuchanong, and S. Techawan (eds.), pp. 321-325.

Coratza, P., and Regolini-Bissig, G. 2009. Methods for mapping geomorphosites. pp. 89-103.

Cramer, L. W. 1963. Pedestal rocks in the Laramie Range, Albany County, Wyoming. Rocky Mountain Geology 2(1): 55-57.

Das, B. 2018. Development of Streambed Potholes and the Role of Grinding Stones. Journal of Environmental Geography 11: 9-16.

De Uña-Álvarez, E. 2008. Description and nomenclature of the tafoni features (cavernous rock forms). Research approaches in granite terrains. Cadernos do Laboratorio Xeoloxico de Laxe

Department_of_Mineral_Resources. 2014. Geology of Thailand. Bangkok, Thailand: Ministry of Natural Resources and Environment.

Duszyński, F. A., and Migoń, P. A. 2022. Skalne grzyby w Polsce i na świecie – terminologia, rozmieszczenie, poglądy na rozwój = Rock mushrooms in Poland and the world – terminology, distribution, views evolution.

Fairbridge, R. W. 1968. The Encyclopedia of geomorphology. Encyclopedia of earth sciences series 3. Stroudsberg, Pennsylvania, Dowden, Hutchinson and Ross.

Fleming, M., and Brand, L. 2019. The role of wind in sediment removal from potholes in semiarid environments. Geomorphology 329: 194-205.

Hong, E., and Huang, E. 2001. Formation of the pedestal rocks in the Taliao formation, northern coast of Taiwan. Western Pacific Earth Sciences 1(1): 99-106.

Horiuchi, Y., Charusiri, P., and Hisada, K.-i. 2012. Identification of an anastomosing river system in the Early Cretaceous Khorat Basin, northeastern Thailand, using stratigraphy and paleosols. Journal of Asian Earth Sciences 61: 62-77.

Jennings, J. 1968. TAFONI, tafone, taffoni Tafoni. pp. 1103-1104.

Jennings, J. N. 1983. Swirlholes and related bedrock river channel forms. Australian Geographer 15(6): 411-414.

Ji, S., Li, L., and Zeng, W. 2018. The relationship between diameter and depth of potholes eroded by running water. Journal of Rock Mechanics and Geotechnical Engineering 10(5): 818-831.

Ji, S., Zeng, W., Li, L., Ma, Q., and Feng, J. 2019. Geometrical characterization of stream potholes in sandstone from the Sunxi River (Chongqing, China) and implications for the development of bedrock channels. Journal of Asian Earth Sciences 173: 374-385.

Kale, V., and Shingade, B. S. 1987. A morphological study of potholes of Indrayani knick point (Maharashtra). Explorations in the tropics: 206-214.

Laity, J. 2014. Pedestal Rock. In H. Hargitai, and A. Kereszturi (eds.), Encyclopedia of Planetary Landforms, pp. 1-4. New York: Springer New York.

Lindholm, R. C. 1987. Sedimentary rock classification. In R. C. Lindholm (ed.), A Practical Approach to Sedimentology, pp. 184-207. Dordrecht: Springer Netherlands.

Marchetti, M., Coratza, P., and Carton, A. 2005. Guidelines for geomorphological sites mapping: Examples from Italy. Géomorphologie : relief, processus, environnement 3

Meesook, A. 2011. Cretaceous. In M. F. Ridd, A. J. Barber, and M. J. Crow (eds.), The Geology of Thailand, pp. 169-184. London: Geological Society of London.

Miall, A. D. Lithofacies Types and Vertical Profile Models in Braided River Deposits: A Summary.

Miall, A. D. 1977b. A Review of the Braided-River depositional environment. Earth-Science Review 13: 1-62.

Miall, A. D. 1985. Architectural-element analysis : a new method of facies analysis applied to fluvial deposits. Earth-Science Review 22: 261-308.

Nemec, W., Lorenc, M., and Saavedra, J. 1982. Potholed granite terrace in the Rio Salor valley, western Spain: a study of bedrock erosion by floods. Tecniterrae S-286: 1-16.

Nocita, B. W. 1986. Pedestal rocks in the Pliocene Puye Formation, New Mexico. Sedimentary Geology 49(3): 193-200.

Potter, P., and Pettijohn, F. 1977. Paleocurrents and Basin Analysis.

Racey, A. 2009. Mesozoic red bed sequences from SE Asia and the significance of the Khorat Group of NE Thailand. Geological Society London Special Publications 315: 41-67.

Reynard, E., Fontana, G., Kozlik, L., and Scapozza, C. 2007. A method for assessing "scientific" and "additional values" of geomorphosites. Geographica Helvetica 62: 148-158.

Reynard, E., Perret, A., Bussard, J., Grangier, L., and Martin, S. 2015. Integrated Approach for the Inventory and Management of Geomorphological Heritage at the Regional Scale. Geoheritage 8

Richardson, K., and Carling, P. 2005. A Typology of Sculpted Forms in Open Bedrock Channels.

Sato, S., Matsuura, H., and Miyazaki, M. 1987. Potholes in Shikoku, Japan, Part I. Potholes and Their Hydrodynamics in the Kurokawa River, Ehime. **愛媛大学教育学部紀要. 第 III 部, 自然科学**

Sattayarak, N., Srigulwong, S., and Patarametha, M. 1991. Subsurface stratigraphy of the non-marine Mesozoic Khorat Group, NE Thailand.

Sellier, D. 2010. L'analyse intégrée du relief et la sélection déductive des géomorphosites : application à la Charente-Maritime (France). Géomorphologie : relief, processus, environnement 16

Sparks, B. W. 1972. Geomorphology (2nd edition). London: Longmans.

Thanh, V. Q., Roelvink, D., van der Wegen, M., Reyns, J., Kernkamp, H., Van Vinh, G., and Phuong Linh, V. T. 2020. Flooding in the Mekong Delta: the impact of dyke systems on downstream hydrodynamics. Hydrology and Earth System Sciences 24: 189-212.

Trexler, J. H., and Cashman, P. H. 1990. Computer-assisted Paleocurrent Determination from Trough Cross-stratification. Computers & Geoscience 16: 253-261.

Tucker, M. 1988. Techniques in Sedimentology. Blackwell

Twidale, C., and Romaní, J. V. 2005. Caves and tafoni. Landforms and geology of granite terrains, pp. 235-257. London: Balkema.

Udomsak, S., Choowong, N., Choowong, M., and Chutakositkanon, V. 2021. Thousands of Potholes in the Mekong River and Giant Pedestal Rock from North-eastern Thailand: Introduction to a Future Geological Heritage Site. Geoheritage 13: 1-17.

Wang, X.-k., Wang, B.-j., Liu, X.-n., and Zhang, L.-q. 2016. Effects of river width changes on flow characteristics based on flume experiment. Journal of Mountain

Science 13(2): 361-368.

Zen, E. A., and Prestegaard, K. 1994. Possible hydraulic significance of 2 kinds of potholes – examples from the Paleo-Potomac River. Geology 22

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